NASA Control No. 10-126

94 p.

N63 20192
CODE-1

Final Report

EVALUATION OF LUNAR GRAVITY NEEDS AND GRAVITY METER CAPABILITIES

Contract No. NASw-581

5 July 1963

Prepared for:

National Aeronautics and
Space Administration
400 Maryland Ave., S. W.
Washington 25, D. C.

OTS PRICE

XEROX $ 8.60 ph

MICROFILM $ 3.02 mf.

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TABLE OF CONTENTS

B. Surveying Problems on the Moon
C. Extract from Texas Instruments Proposal No. A63-93

LIST OF ILLUSTRATIONS

of whether there is a structural difference between the lunar maria and the terrae, as exists (though not analogously) between terrestrial continents and ocean basins. An orbiting satellite would give further data on the subject, provided that the state of lunar exploration would permit accurate tracking.

Finally, gravity traverses made on the surface with roving vehicles would provide the key to the structure of craters and other local features in much the same way as such traverses do on the earth -- with one major difference. In terrestrial exploration, structural understanding is largely based on sedimentary stratification, and the primary facility for it is erosional exposure. Since atmospheric and water erosion are absent on the moon, lunar stratification differs widely in nature and scope from its terrestrial counterpart. (See Shoemaker and Hackman, 1960, and Hackman, 1962). The key to structural interpretation will be density, and the prime geophysical exploration instrument will be the gravity meter. As long as density contrasts are present, gravity will yield the first evidence as to the substructure of lunar features, and will probably answer many questions now under debate, such as the existence of isostatic compensation and the volcanic origin of certain craters and domes.

Task 3

The different methods of geophysical exploration are interdependent; knowledge gained through one of them supplements knowledge gained through the others rather than substituting for it. The primary requisite for all geophysical interpretation is good surface mapping and valid study of the surface geology. The first of these will probably be based on sets of photographs taken from low-altitude lunar orbits and interpreted photogrammetrically as accurately as the data allow. Surface geology will proceed as far as possible from these data but will also require work on the ground with sampling and physical and chemical analysis of surface materials. The absence of severe erosion and the consequent preservation of surface structures, gives surface geology a power on the moon that it does not have on the earth.

Seismology will give important information about the moon's internal constitution, just as it does for the earth, and measurements of seismicity will give valuable evidence as to any geologic processes now in operation. In the exploration of local terrestrial structures, seismology depends for its unique strength and versatility on the depositional stratification of earth materials. Since lunar materials are not stratified in this way, seismology will not play the dominant role in local exploration on the moon. Normally gravity anomalies will be examined with the seismograph if they are ascribed to large masses; however, exploration seismology on the moon may be severly handicapped by the presence of unsorted coarse material in the transmission paths. When such material is encountered in

INTRODUCTION AND SUMMARY

This report is a study of the use of gravity meters on the moon. It treats (1) the scientific problems which can be solved or partly solved with gravity observations, (2) the relations and interdependence between gravity and other geophysical methods of getting information about the moon, (3) the successive observational modes and instrument types to be used as lunar exploration technology advances, and (4) the present state of gravity-meter art and the relative merits of different principles and designs for use in fabricating a hard-landing lunar meter. The report is divided into sections that are labeled tasks in conformity with the statement of work of the contract under which the study was performed. The findings under each task are summarized below.

Tasks 1 and 2

Task 1 is to list the problems in lunar exploration that are soluble or partly soluble with gravity data. Task 2 is to examine the accuracy of the results as a function of the accuracy of the lunar gravity measurements obtained. These two tasks are not logically separable and are therefore reported together. It was found that a single gravity meter landed on the moon would permit the measurement of earth-caused tides due to the moon's monthly change in orbital distance from the earth. The forces acting to produce these tides are known, so that an observation of their amplitude would be a measure of the moon's rigidity. If the meter were landed near the limb and the elevation of its landing spot were known, it would give a more accurate value for the moon's mass than is now known. With a properly constructed read-out device the gravity meter could also act as a seismometer and thus provide data as to the moon's seismicity.

A second gravity meter, if it were landed near the center of the visible disc, would give an indication of the magnitude of the "bulge", now the subject of considerable disagreement - provided certain assumptions now generally held about the moon's density are true. It would also institute work on the problem of selenodesy, or the figure of the moon. (In this report the choice between expressions like "selenodesy" and "lunar geodesy" will be based on rhetoric; sometimes one form seems more appropriate and sometimes the other. Geophysics, for instance, is mainly a set of techniques, while geodesy is mainly a body of specific information.)

If gravity meters can be made sufficiently small and reliable, they will probably be carried routinely on moon-bound spacecraft because of the important additions to lunar science which can be deduced from each successive observation. The third, fourth, and fifth gravity readings, besides greatly refining the selenodetic picture, will tend to answer the question terrestrial exploration it scatters the energy badly and precludes the use of ordinary seismic methods.

Heat flow and radioactivity are evidence of operating geological processes and of deposits of valuable materials. The absence of thick sedimentary layers will make thermal and radioactivity measurements easier to carry out and interpret. Electrical measurements will also be easier to interpret than they are on earth in the presence of low-resistivity layers and so may have a wider scope on the moon. Magnetism will be an effective tool only if the moon proves to have a perceptible magnetic field (now thought not to be the case) or if a method of using space magnetic fluctuations as signals is developed.

Task 4

The stages in lunar exploration each call for different types of gravity meters and different modes of operation. These are summarized as follows:

1. Hard-landing spacecraft require a gravity meter that is (a) extremely rugged -- to withstand landing shock and (b) extremely simple -- because complicated mechanisms are vulnerable. It must, of course, telemeter its readings.

2. Soft-landing spacecraft permit a meter to be more accurate, e.g., as regards calibration, and more versatile, as a seismometer or tidemeter. Telemetering is still required.

3. A manned spacecraft will permit gravity traverses to be made on the surface in the usual terrestrial way, although optical surveying for elevation will be difficult because of the short visual range due to the smaller radius of the moon. This disadvantage will be offset by the clarity due to the absence of air, so that finer optical instruments can be used and long shots taken from mountain peaks.

4. An orbiting spacecraft will itself be a gravity meter if it is tracked with sufficient accuracy in its orbit to detect perturbations.

5. A roving unmanned vehicle will be able to carry an automatically reading gravity meter, gradiometer, and survey log, thus providing a wide scope for exploration traverses.

6. A manned roving vehicle will be more expensive than the unmanned vehicle, but with a gravity and gradient read-out

computed as the observations were made, it could be used to explore anomalies as they were observed.

7. A hovering (not orbiting) spacecraft would use an airplane gravity meter of the type now being developed and be able to make a gravity network of the entire moon.

Task 5

Gravity instruments are examined to see which of the principles and devices now known would be the most suitable for near-future incorporation into a hard-landing spacecraft package. Known devices include sensors based on quartz elastic members, metal elastic members, pendulums, and vibrating strings. Principles on which accelerometers have been built, but not used as gravity meters, include piezo-resistance and piezo-electric effects. Gradiometers are also discussed. It is concluded that the design based on a quartz elastic member is best suited for near future development as a feasible device. The reasons are that (1) the quartz design offers the best resistance to the hostile environment that will be encountered, and (2) experiments and testing for shock resistance and temperature compensation have proceeded far enough so that success with the device can be reasonably anticipated.

CONCLUSIONS AND RECOMMENDATIONS

1. It is concluded from the present study that gravity can play a dominant role in all stages of lunar exploration, from the first steps in selenodesy down to detailed exploration of specific areas. For several reasons gravity will have a relatively greater importance for lunar exploration than for the same function on the earth. It is therefore recommended that steps be taken to make gravity observations as often and as accurately as the national space program will permit. It is also recommended that a continuous program for developing gravity meters be carried out so that suitable gravity meters are available when the spacecraft are. The development will be most effective if it is carried out as a series of key experiments to test successively the effectiveness of vital components.

2. The gravity meter best adapted to present transport in a hard-landing lunar spacecraft is one based on a quartz elastic member. This instrument is so far advanced in testing and development that it can reasonably be expected to be successful. It is recommended that the development of this meter be pressed so that it may be transported to the moon in an early flight.

TASKS ONE AND TWO: SCIENTIFIC KNOWLEDGE FROM LUNAR GRAVITY DATA, RESULTS AND RELIABILITY

A. GRAVITY AS A SCIENTIFIC TOOL

Task One in the present study is defined as "a detailed investigation of scientific problems that could be solved or profitably investigated by gravity meters or gravity gradiometers" on the moon. The best way to begin an inquiry into such problems is to review the role which gravity measurements have played and are playing in the study of the earth. The problems gravity measurements will solve or help to solve on the moon are the same as the ones they have solved and are still solving on the earth, with the difference that such measurements will be of greater significance on the moon. This is because stratigraphy, the key to much of earth structure, is absent on the moon, and students of lunar geologic structure will have to get most subsurface information by methods not based on sedimentary stratification. The most powerful of these methods is gravity. In addition, gravity may be observed anywhere on the moon (as far as we know) without hindrance from surface features such as the terrestrial oceans.

Gravity was first recognized as one of the most important keys to knowledge about the earth when it was noticed that pendulum clocks kept time differently when they were moved from one latitude to another. The explanation was found to be that the earth's radius varies from one part of the earth to another - that is, the earth is not a sphere but a speroid. Thus, in the seventeenth century, the science of geodesy was born. Three centuries later we are still using gravity to discover the finer details of the shape of the earth. Recently geodesy has been substantially forwarded by observing the effect of gravity on artificial satellites as well as on gravity sensors on the earth's surface. Much remains to be learned, however, from both methods.

Geophysics on a continental scale was the next stage in earth science after the advent of geodesy. Not long after the variation in the period of pendulums was observed, it was noticed that while mountains pulled plumb-bobs toward themselves, as predicted by the law of gravitation, the amount of the pull was less than was expected. The explanation lay in the fact that the mountain did not constitute as much extra mass as was apparent, because its roots were lighter than the surrounding rock. Thus the study of crustal geophysics was begun -- with the discovery that heavy material lies under the oceans and lighter materials under the continents. An intimate relation has to exist between this distribution of mass and the observed gravity; gravity is therefore a partial index to the thickness of the crust. (Woollard, 1959; Steinhart and Meyer, 1961).

For the needs of geodesy and crustal geophysics, the relatively crude measuring devices of the eighteenth and nineteenth centuries gave valuable information, though much has been discovered in the field since then with the aid of more accurate instruments. The details of local structure, however, could not be studied with gravity because their gravitational effects were too weak. With the invention of the Eötvös torsion balance, near the turn of the century, a new age in geophysics was opened. Evidence of the presence of small-scale geologic structure invisible from the surface was now available, provided only that a density contrast existed. The torsion balance was followed by the field gravity meter, and it by seaborne and airborne gravity meters and gravity meters that detect earth tides. There are now almost no limits to where and how accurately gravity can be measured on the earth. Its application is limited by the ingenuity of the interpreter and by the accuracy of navigation rather than by gravity measurement itself. Gravity anomalies of all magnitudes are observed everywhere, each one evidence of a geologic phenomenon.

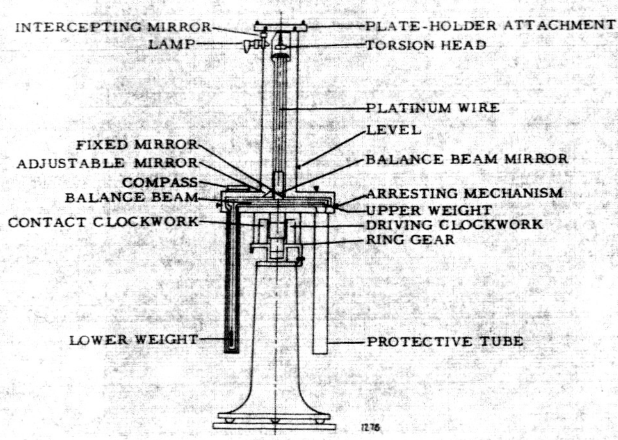

Figure 1. Eötvös Torsion Balance (After Jakosky, 1960)

The conquest of the moon is now under way. We have a set of readymade geophysical tools for acquiring quickly the same kind of knowledge we took so long to collect about the earth. Perhaps the most versatile of these tools is gravity.

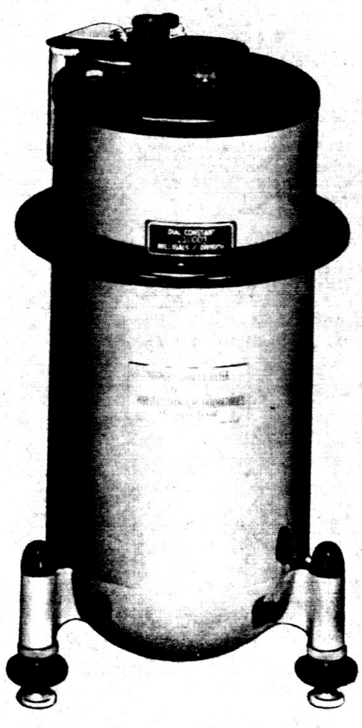

Figure 2. WORDEN* Gravity Meter

*Trademark of Texas Instruments Incorporated

B. GRAVITY AT A SINGLE POINT

1. The Technical Problem

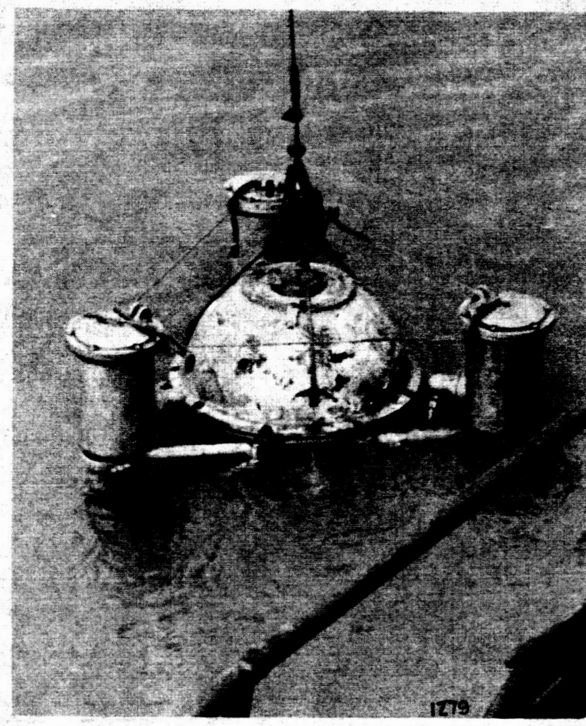

Figure 3. Seaborne Gravity Meter

The most difficult technical problem in the entire lunar gravity program is of course to land the first gravity meter on the moon in an operating condition and to receive its reports. Some engineering aspects of the problem are discussed in the section on Task 5 of this report. In order to evaluate the usefulness of the reading from a single gravity meter, we shall assume that it will give absolute gravity with a calibration error of $\pm$ 5 milligals and relative gravity (that is, from one time to another) of $\pm$ 0.5 milligal. These accuracies are not, of course, demonstrably attainable now. Enough experiments have been performed to show that they are a reasonable estimate of what could be obtained with the aid of a succession of key experiments followed by appropriate modification of the components of the meter.

2. Tides and Elasticity

A single gravity meter, landed in the center of the moon's visible disc, would be located at the spot most favorable for measuring the amplitude of the solid tide of the moon. A location near the limb would also be in a tidal zone. A location halfway between would be intermediate as far as the earth-produced tides were concerned.

A gravity meter on the surface will respond to the variation of the tidal force in two ways. First, it registers the change in milligals in the local gravity due to the change in position of the heavenly body that causes the influenced body to yield in response to it - and all bodies must yield as none are infinitely rigid - the meter is lifted farther away from the center of the body on which it stands and will therefore give a smaller gravity reading. The first change can be computed from astronomical data. The second effect is therefore the total effect minus the first. It is equal to the vertical derivative of gravity times the yielding; the yielding can therefore be computed and used as a measure of the bulk elasticity. For a treatment of the relation between the yielding and the elasticity, see Tomaschek, (1957).

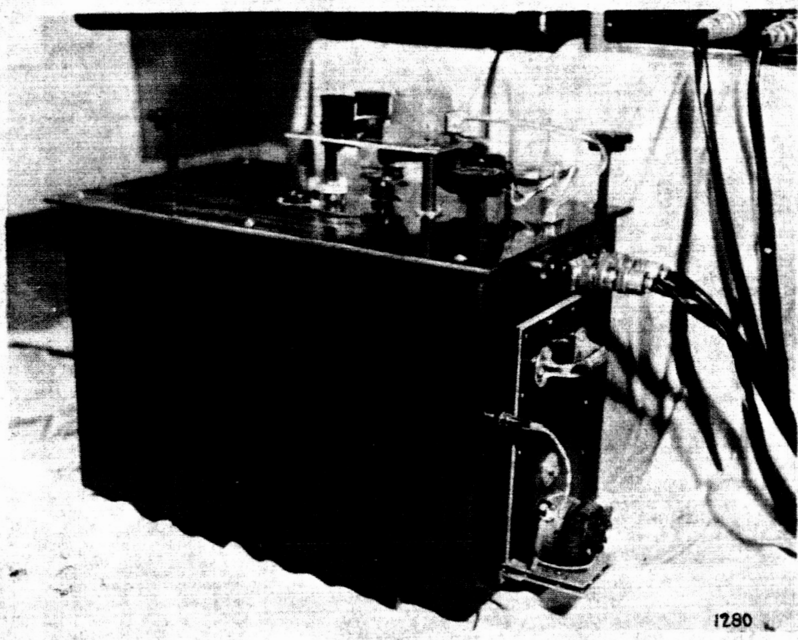

Figure 4. La Coste-Romberg Earth-Tide Meter

The maximum change in tidal force on the earth is about 0.3 milligal, a little more than two-thirds of this being due to the moon and the rest to the sun. In order to observe the yielding of the earth to these forces, a set of observations was conducted by Baars (1953) lasting a month and located at 21 stations scattered all over the world. The result was that the observed change in gravity was only a quarter larger than the computed change in force; the rigidity is thus very high. The actual yielding of the solid earth to the tidal forces is in the neighborhood of one foot.

In order to describe the tides on the moon, it is convenient to begin with a review of the time cycle and relative magnitudes of tides on the earth. The principal factor causing the change in tidal forces on the earth is its rotation. This gives the tides due to the sun a double cycle every 24 hours, and the tides caused by the moon a double cycle almost 25 hours long, the longer cycle being due to the motion of the moon it its orbit. The cycle is double rather than single because of the dynamics of the situation. The tidal force at the earth's center is zero, since it is in free fall toward the tide-producing body. Another way of stating this is that the attraction of the other body is exactly cancelled by the centrifugal force due to the orbital motion of the earth's center about the center of gravity of the earth-moon (or earth-sun) system. On the surface facing the tide-producing body the distance is less and the attraction is therefore stronger, giving a net force upward; on the surface away from it the attraction is weaker, giving a net force that is also upward at that point. The result is that there is a high tide on the surface both toward and away from the tide-producing body, and a low tide in the zone between. (Figure 5).

The other cause of change in tidal forces is the variation in distance. In the tides due to the sun this is not large enough to be important, but in the tides due to the moon the forces change noticeably, causing the high-amplitude _spring_ tides at perigee and the low-amplitude _neap_ tides at apogee.

On the moon the tides caused by the sun change in the same way as on the earth, that is, a double cycle for every lunar day. The effect is only one-quarter as large due to the moon's smaller radius, so that their amplitude in terms of gravity is only 0.01 milligal. The tides caused by the earth are not affected (except in the second order) by rotation, so that high and low tides do not occur in a given location but only springs and neaps. The computed difference between spring tide and neap tide is about one milligal for the center of the visible disc. (See Appendix A). The unknown quantity is of course the extent to which the surface yields under the change. Urey and others (1959) reported that for a liquid or completely yielding moon the motion would be 16.2 meters. The number of milligals this corresponds to can be computed roughly from the vertical gradient of gravity. We have

$$-\partial g/\partial r \doteq 2g/r = 324.6/1.738 \times 10^{8} = 0.187 \text{ mg/meter}.$$

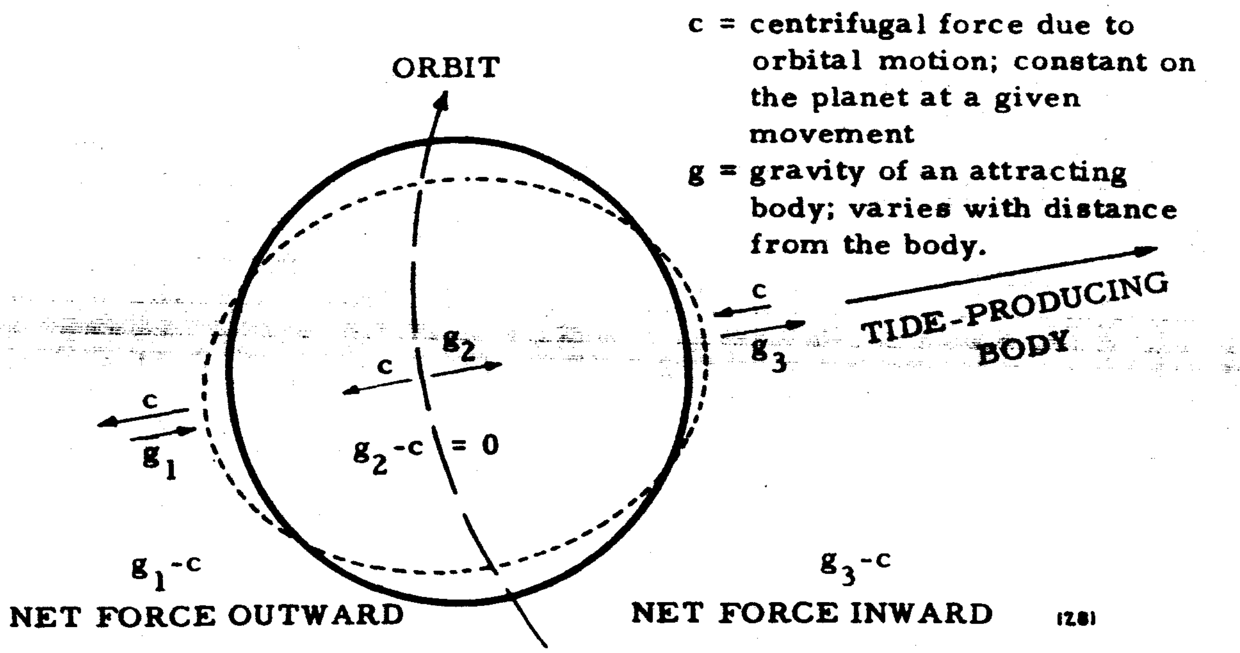

Figure 5. Tidal Forces On The Surface Of A Planet

The maximum change in gravity due to the yielding would be -3 milligals, making a possible total of -4. If the precision of the meter is ± 0.5 milligal, a useful piece of information would result from readings of the tide.

The principal utility of a knowledge of the tidal yielding would be an insight, at least a preliminary one, into the moon's structure. Urey and others (1959) and Macdonald (1961, 1962) mention the possibility that the moon, having been produced by a sort of agglomerative process, lacks the molten core and plastic isostatic mechanism which so extensively govern the history and behavior of the earth. This hypothesis is supported by the low mean density (3.34) of the moon, but is partially contradicted by the evidences of volcanic action and lava flows (Baldwin, 1949, and Green, 1962) that are observed on its surface. A change in the tidal gravity of 1.5 or 2 milligals would favor the plastic or molten-core theory, while a change of 3 or 3.5 milligals would weaken it.

3. Seismicity

A gravity meter which reads with a precision of ± 0.5 milligal would be useful as a seismograph if high-frequency changes in the position of its beam could be telemetered. The displacements to which it would respond would be a function of the period of the displacements. The moving system of the instrument would probably have a free period of one second or less, and a change in the acceleration of 0.5 milligal would correspond to a displacement of about 10^{-5} centimeter or 0.1 micron. For longer periods the minimum displacement sensed would be proportional to the square of the period, so that for seismic energy with a period of 10 seconds the minimum perceptible displacement would be 10^{-3} centimeter or 10 microns. These levels of sensitivity would represent high seismicity or the occurrence of small earthquakes on the earth. If the tidal yield on the moon is anything near the maximum, it is highly probable that there will be a considerable degree of local seismicity in the high-tide areas, i.e., the bulge, the anti-bulge, and the limb zone. A "quiet" earth has a general seismicity level of a few millimicrons, so that if the moon is similarly quiet the gravity meter of the postulated sensitivity would register only moonquakes, lesser disturbances being below its threshold level.

Lunar seismicity can be divided into three categories, i.e., (1) meteorite impacts, (2) tectonic seismicity of the terrestrial type, and (3) seismicity due to tidal yielding. The third could be distinguished from the other two by its cyclic character; it would have dead periods as the tidal forces passed their maxima or minima. Distinguishing between meteoritic and tectonic seismicity will probably depend on the observation of shear waves and will be beyond the power of a single short-period seismometer (Lehner and others, 1962).

4. Mass of the Moon from Gravity

The ratio of the moon's mass to that of the earth was reported by Brouwer and Clemence (1961) as 81.366 ± 0.029, an accuracy of one part in 2800. If the mass is known with that accuracy then the proposed new determination of it with a gravity meter would be of only routine interest. Recently, however, the error was reported by the same authors (1962) to be one part in 800, and by Grushinskii and Sagitov (1962) as one part in a thousand. If this error could be reduced - say to one part in four thousand - with a gravity reading, the result would be important. The probable error in predicting surface gravity on the moon, according to the above references, is plus or minus 200 milligals. If the surface gravity could be read with a substantially smaller error, a better determination of the moon's mass would result.

The limiting factor in observing lunar surface gravity will be the uncertainty in determining the elevation of the recording point with respect to the average surface in the neighborhood. This uncertainty (see the following paragraphs) will perhaps raise the probable error of the surface-gravity observation to plus or minus 10 milligals. To compute the mass from the surface gravity, however, we need to know the radius. According to the last two publications referred to, the error in the radius is ± 200 meters or about one part in 9000. Since

$$M = \frac{r^2 g}{k}$$

(where m = mass, k = gravitational constant, g = gravity, and r = radius)

the error in mass would be one part in 4500. This is substantially better than one part in a thousand and indicates that the best location for the first gravity meter landing is on the limb where the radius can be most accurately observed. If between now and the time the experiment is performed a better determination of the mass is made, the landing should be made in the center instead of on the limb, in order to determine the magnitude of the bulge. (See section C below).

The local elevation of a gravity observation must be known before the observed value can be used in interpretation. This is of course because of the very considerable effect that elevation alone has on gravity. By "local elevation" is meant the elevation relative to the mean ground level or selenoidal surface of the general surrounding area. For terrestrial gravity exploration the local elevation should be known, relative to the prospect at least, to an accuracy of a few centimeters, but this is for gravity meters that are read to 0.01 milligal. Since we expect only ± 5 milligals (absolute) of the lunar meter the requirement of accuracy is relaxed in proportion, but it is still one of the limiting factors.

The theory of reducing gravity observations in order to remove irrelevant effects, so that interpretation can proceed, is well known. (See Dobrin, 1960, Chapter 11). In a first approximation, the elevation correction consists of two parts, (1) the vertical gradient or free-air correction, and (2) the so-called Bouguer correction to account for the extra mass of ground beneath an instrument which is on a hill or mountain.

The vertical gradient is given by the formula

$$\frac{\partial g}{\partial r} = - 0.187 \text{ mg/meter}$$

negative because the distance from the moon's center increases with elevation, thereby decreasing the gravity; since the effect is negative the correction is positive. The Bouguer correction is usually taken to be the downward attraction of a slab of material inserted between the base elevation - sea level or some other - and the observation point. It is computed from the attraction formula

$$\frac{\Delta g}{\Delta h} = 2\pi ks$$

where k is the gravitational constant, s the density of the surface material, and h the elevation. If s = 2, a usual value for terrestrial surface materials, the Bouguer correction will be

$$\frac{\Delta g}{\Delta h} = 0.084 \text{ mg /meter}$$

Since the effect is positive the correction is negative. The combined elevation correction is then - 0.103 mg /meter. (Figure 6) A gravity meter read to ± 5 milligals would require an elevation known to ± 35 meters if the probable error due to the elevation uncertainty were not to exceed ± 6 milligals, or an elevation known to ± 87 meters if the total uncertainty were to be held to ± 10 milligals. Kopal (1961) states that in certain cases it is possible to measure from earth the relative elevation of a lunar topographic feature to ± 10 meters. It is beyond the scope of the present report to examine the validity of this figure, which would probably not prove to be representative anyway for the case of a particular landing spot. However, it does not seem unreasonable to expect that if the landing location can be observed at all, its elevation could be determined accurately enough to give gravity to ± 10 milligals.

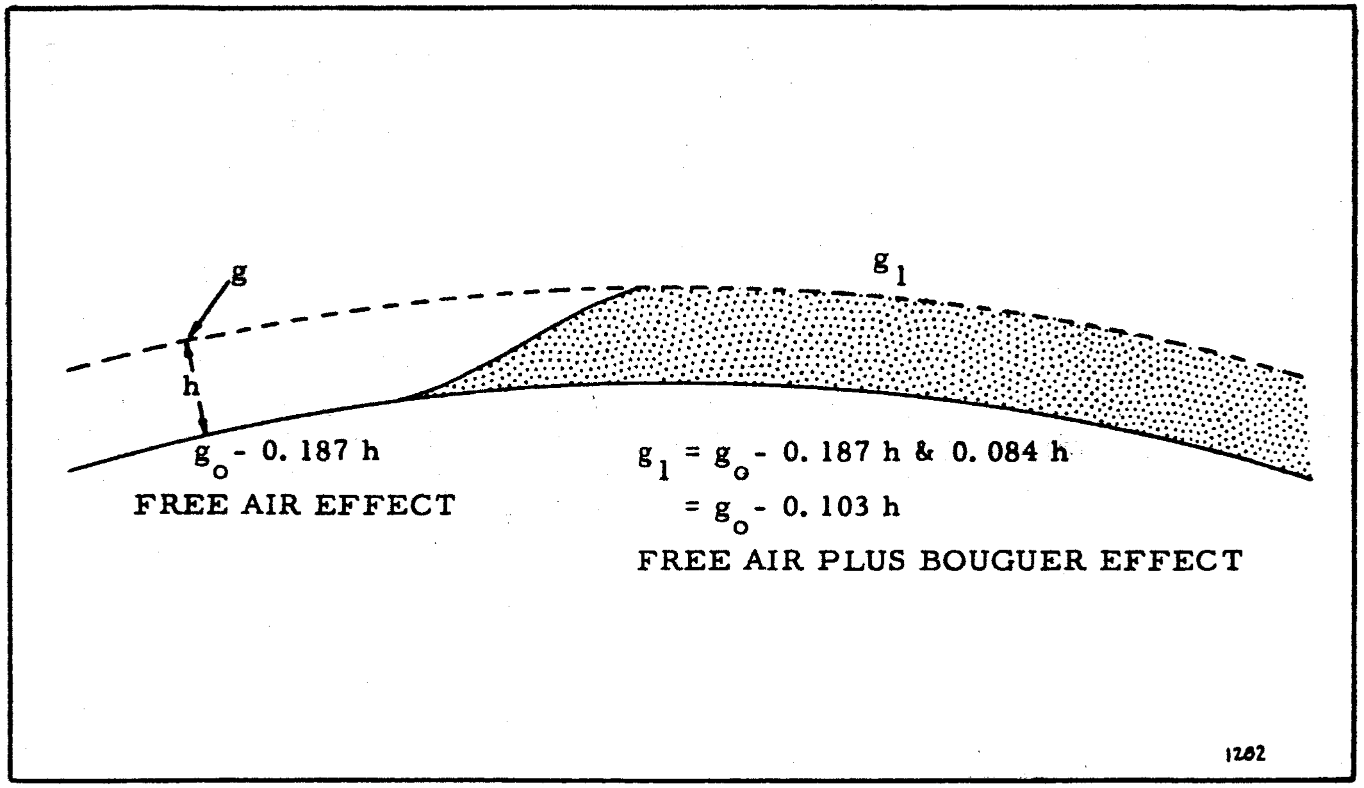

Figure 6. Free Air And Bouguer Effects

C. GRAVITY AT A SECOND POINT

1. Normal Gravity on the Moon

Once the moon's surface gravity at a representative point is known, it will be possible to predict the "normal" gravity at any point on the visible surface. Since the moments of inertia about the three principal axes are known relative to each other, a triaxial reference ellipsoid or ideal figure of the moon can be constructed, based on the assumption that density changes radially but not tangentially. The normal or predicted gravity can then be computed as a function of latitude and longitude on the reference ellipsoid. Then if a gravity observation is made and a difference exists between it and the predicted gravity, an anomaly is present and must be ascribed to some excess mass, or lack of it, in the neighborhood.

2. Determination of the Bulge

A conspicuous discrepancy exists at present between different determinations of the earthward bulge of the moon. Three methods of estimating it are used: (1) calculation of the effect of earth-produced tide on a moon in hydrostatic equilibrium, (2) the ellipticity due to the unequal moments of inertia as computed from observations of the motion, and

(3) optical methods. The first of these indicates a bulge of less than 0.1 kilometer, the second about 1 kilometer, and the third more than 2 kilometers. The probable errors of the different determinations do not overlap so that they cannot be reconciled by compromise. The hypothesis which does reconcile them is that the near-surface material at the center of the disc is less dense than the material elsewhere - i.e., near the limb. In order to preserve the calculated relation between the moments of inertia, the radius would have to be greater in that neighborhood. A functional relation must exist between the increased volume occupied by the postulated less dense material and the increased radius necessary to preserve the moment of inertia. The surface gravity is decreased by both these effects. A one-to-one correspondence will therefore exist between the surface gravity on the bulge and the magnitude of the bulge itself. A negative gravity anomaly greater than that predicted for the eccentricity for a regular mass distribution must indicate a greater bulge.

(Note that the triaxial or bulge hypothesis is incompatible with a large tidal yielding. The moon cannot have moments of inertia as different as those observed, and still be in hydrostatic equilibrium. If both a bulge and a large tidal yielding are observed there is a defect in the present theory.)

The relation between the bulge and the resulting gravity anomaly can be found to a first approximation from the vertical gradient. In a figure closely resembling a sphere, the vertical gradient on or outside the surface (there is a discontinuity in the gradient at the surface) is given by

$$\frac{\partial g}{\partial r} = \frac{-2g}{r}$$

if the density varies only radially. The equation holds whether the lifting of the observation point occurs through raising the measuring instrument above the surface or through expansion of the body without changing its mass. The reason for this is the well-known fact that the gravitational effect of a spheroidal shell acts outside the shell as though the mass of the shell were concentrated at its center. As might be expected, the vertical derivative of the gravity of a prolate spheroid, at a point on its axis, approaches that of a sphere as the eccentricity decreased (MacMillan, 1930, p. 17). The derivative at the surface is about 0.19 milligal per meter on the moon's surface, so that if the density is evenly distributed, a bulge of one kilometer would give a negative density anomaly of 190 milligals. If the bulge is composed of less dense material, the anomaly will be even larger, but the bulge will also be larger.

The vertical gradient of 190 milligals per kilometer is large enough so that if the local elevation can be determined so that the observational error is no more than ± 10 milligals, the magnitude of the bulge can be determined to about 50 meters. (If the bulge is larger, due to material of low density, the probable error due to lack of knowledge of the distribution of the low-density material would also be larger.)

3. Possible Influence of Local Anomalies

It is of course theoretically possible for low-density material to exist immediately below a point of observation in such quantities as to give a negative anomaly not representative of either bulge magnitude or low average density. It seems unlikely, however, that this will be the case. On earth, for example, the order of magnitude of observed negative free-air anomalies is in tens of milligals; even in the ocean the free-air anomaly is rarely more than 25 milligals (See Heiskanen and Vening Meinesz, 1958, Chapter 7). There are almost no negative free-air anomalies approaching 200 milligals, and the only positive ones approaching that amplitude are in high mountains. On the moon, with its much lower mass, a low-density structure causing an anomaly of even 100 milligals would be important enough in proportion to affect the moment of inertia.

D. LUNAR GRAVITY NETWORK

1. Methods and Accuracies

A systematic lunar exploration program, having achieved two observations of surface gravity and drawn the conclusions indicated above, would then broaden its scope. Operationally, this could occur in three different ways. First, when a reliable miniature gravity meter for lunar use is developed it will be included as a matter of course in the payload of all moonbound spacecraft because of the additional value of each new observation. Second, a manned orbiting station will logically precede the manned spacegraft landing. The orbit of such a station, computed from observations made by its own passengers will yield a good selenographic gravity net, necessarily on a broad scale but confirming and supplementing (or else contradicting) the general validity of the previous point-observations. Third, individual telemetering gravity meters could be impacted on the surface with relative economy from such a station. The anomalies of particular features could be measured and interpreted with the aid of single-impact readings.

The accuracy of the gravity readings in the network stage of operations would be improved over that of the first meter landings by a factor of perhaps four or five but not by an order of magnitude. The ground instruments would still be subject to the uncertainties of their elevation, and the third, fourth, and fifth landings, for example, would have reduced errors only as the techniques for measuring elevations had improved. Possibly the previously discussed accuracy of $\pm$ 6 milligals could be reached and probably the instruments themselves would be improved by that time. The results from the tracked orbiting station would not be limited by calibration or topography. They would be absolute in the sense that they depend only on the altitude and velocity of the orbit. The limiting factor in tracking results would be the accuracy of the tracking apparatus, which would consist of a combination of Doppler radar and carefully timed photographs. (See Appendix D) The velocity of a near-surface orbit is about 1.7 kilometers per second, but the propotional error in gravity will be twice the proportional error in velocity.

$$g = v^2/r$$

$$\partial g = \frac{2v\partial v}{r}$$

$$\frac{\partial g}{g} = \frac{2\partial v}{v}$$

To give the gravity to ± 10 milligals, or one part in 16000, the velocity would have to be known to one part in 32000. This is far beyond the capacity of present radar systems; it is possible that accurately timed photographs will provide the best velocity data. (Sci. Am. Aug. 60).

The orbiting station would of course provide a much better way of measuring surface elevation than was previously possible. The gravity meters which it would impact on the surface, and probably the meters which had landed from spacecraft in the previous stage, could probably be located to ± 10 meters in elevation -- an error which would affect gravity with an uncertainty of only one milligal. This would permit recalculation of the readings of these meters and reduce the errors substantially to the calibration error only.

The magnitude of the gravity anomalies to be expected in the network stage can at present be only a matter of speculation, but since lunar topographic features exist on the same scale as terrestrial features, the anomalies will doubtless be of the same scale also, especially since the leveling influence of erosion is not present. (One reason why earth gravity meters must be so accurate is that they are usually used in sedimentary basins where uniformity is the rule, with the result that the anomalies are small.) A guide to the range of terrestrial surface anomalies can be found in Heiskanen and Vening Meinesz (1958, Ch. 7), where various lists of free-air anomalies are given. They are of the order of 10 to 100 milligals, with larger ones occasionally in the larger mountain ranges.

2. Problems on the Origin of the Moon

As soon as a lunar gravity network has been established, with its combination of average anomalies over regions and particular anomalies of large features, a significant advance can be made in lunar theory, especially in the hypotheses of lunar history. These hypotheses vary generally from the cold-moon agglomeration theory (Urey, 1962), through in-between theories requiring ancient volcanism (Green, 1962) to theories that call for a molten core and interior convection (Runcorn, 1962) and a volcanic history similar to that of the earth. In general the cold-moon theories imply that the density, at least that of crustal and sub-crustal material, varies widely and more or less unsystematically, with no tendency toward homogeneity (except insofar as the agglomerations resemble each other) and abrupt instead of continuous adjusting mechanisms. In general the hot-moon theories imply that the gravity anomalies are similar to those on the earth - a good guide to the reference ellipsoid and to the more or less systematic division of the surface into the great categories of continents and oceans.

As a guide to the possible course of gravity interpretation on the moon, consider Urey's (1962) article on the Origin and History of the Moon. Almost every suggestion he makes or conclusion he draws implies a density condition which would give rise to a gravity anomaly. Some of these suggestions will be discussed here as examples.

a. "The high mountains on its surface show that the subsurface regions are not plastic at the present time, nor have they been so at any time since the mountains were formed." If this is correct, the Bouguer anomaly will be small, say 10 milligals, and the isostatic and free-air anomalies large, say 100 milligals; if the interior is plastic, the Bouguer anomaly will be strongly negative, say 200 milligals, the isostatic anomaly small, and the free-air anomaly in between. (The free-air anomaly is the observed gravity compensated only for the vertical gradient, the Bouguer anomaly is the residual after compensation for the visible topography of the meter location, and the isostatic anomaly is the residual after compensation for sinking into the plastic sub-crust.)

b. "If the density varies with latitude and longitude, it is possible to account for the irregular shape even if the deep interior does not have great rigidity." This question has already been touched on in the discussion of low-density material in the bulge. The existence of known moments of inertia in a low-rigidity body imposes conditions of compatibility in the local densities; these would give rise to anomalies on the order of 200-400 milligals for the different estimates of the bulge.

c. "It is concluded that the moon was accumulated at low temperature with only local or temporary melting, ... that the lavas resulted from high-energy collisions with its surface and are not the result of subsurface melting..." Lava bodies give typical gravity anomalies on the earth, sometimes with indication of crossed faults and a stock or feeder. A lava body produced by a collision would not have these features.

E. GRAVITY TRAVERSES AND LOCAL ANOMALIES

1. Techniques and Precision

When lunar exploration reaches the stage of landing a manned spacecraft on the surface, geophysical exploration will have reached a stage where terrestrial techniques can be used and terrestrial accuracy achieved. The selenodetic gravity field can be accurately mapped by ground-based tracking of satellites and orbiting stations, so that results from the previous stage can be greatly refined - most important, gravity meters will now be readable to the 0.01 milligal precision as in everyday practice on the earth, and gravity traverses consisting of a station every kilometer or every ten meters can be made depending on the size of the feature being investigated.

The precision of ± 0.01 milligal, to which regular gravity meters are read is by no means the limit of accuracy possible for such instruments; microgal meters, for example, are in use for special purposes such as reading the tides. The limit of one hundredth milligal is set by the "noise level" of ordinary topography. In the search for local structures the effects of ditches, banks, fills, minor watercourses, and such topographic features can usually be kept to the level of one to two hundredths milligal by judicious placing of the observation points. In country that is moderately hilly the effects of the hills and valleys can usually be computed to about the same accuracy. For this reason, portable meters are customarily built to be read with no higher precision. Instruments for ground use on the moon would no doubt be made exactly like those now used on the earth except for temperature shielding and some form of automatic recording of the readings. The question of meter transport and the necessary leveling for station elevations is discussed later in this report.

The techniques of geological exploration with gravity are well known so that there is no need to discuss them here in detail. The principles are covered in textbooks on geophysical exploration, of which the newest are by Dobrin (1960), Jakosky (1960) and Parasnis (1962). Nettleton (1942) and Lyons (1956) have edited collections of case histories, and a recent review and bibliography was published by Romberg (1961). There is an extensive technical literature on the subject, and at least two books (Romberg and Geyer, Fraser Grant) are in preparation and will probably appear in 1964. The process of gravity exploration consists essentially of the following steps:

(a) observe the gravitational field in appropriate detail, (b) identify and separate the anomalies in it, (c) ascribe the anomalies to geological features likely to be present, (d) match the observed anomalies with the gravity of computed models to support the ascription. Interpretation of gravity data yields no unique solution; the solution is only the most likely one.

Local anomalies, as the phrase is used in this section, consist of all anomalies not conveniently measurable by single-meter landings or satellite tracking. This includes, for practical purposes, all anomalies less than perhaps 100 kilometers in horizontal dimensions, ranging from the anomalies of subcontinental features down to irregularities a few tens of meters across. They can be roughly classified, from small to large, as (a) near-surface irregularities, (b) accumulations and deposits, (c) minor structures, and (d) major structures. This will be discussed briefly in turn.

Incidentally, when manned spacecraft landings are achieved, a regular recording microgal gravity meter should be set up for accurate reading of the tides. Such meters are in regular use (Clarkson and LaCoste, 1957) for measuring the phase and amplitude of tidal motion. By suitable filtering of their output they can be used as long-period seismometers.

2. Near-Surface Irregularities

An immediate use for the gravity meter after the first manned landing will be to determine the nature of the surface. The surface density can be measured by making short traverses over ground irregularities and finding the density which compensates exactly for their effects. Caves or regions of porosity or vesicularity can be discovered with gravity readings if they are large enough or close enough to the surface (Romberg, 1961b). An abrupt change in the surface gravity is evidence of structure, change of composition, or change in physical state, close to the surface, so that before using drills or physical probes local surveys should be made with accurate gravity meters.

3. Accumulations and Deposits

An accumulation or deposit of material of different composition from the surrounding rock nearly always has a different density, and if the density is different a gravity anomaly will be present. Numerous examples of the discovery of depositis of material can be found in the technical literature, notably in the case histories referred to above. Salt domes are an example of large-scale masses of material found by gravity, and metallic ores such as magnetite and chromite are examples of small-scale masses.

The smaller masses are detectable with gravity only if they are fairly close to the surface because their anomalies decrease rapidly with depth. There has been some speculation (Firsoff, 1959)) about the possibility of substances such as ice being found not far under the lunar surface. If it were present in any quantity ice would probably give a strong negative gravity anomaly. Metallic ores are usually heavier than the surrounding rock and thus give positive anomalies.

4. Minor Structures

a. Selenology

Minor structures (for the purposes of this report) are those structures small enough to be studied with the methods of geology and geophysics by the first investigators to reach the moon's surface and be able to walk about on it. The minor structures are so defined in contrast with the major structures such as the maria and the larger craters, which because of their areal extent will require long-range vehicles for their exploration. A considerable interval will ensue between the first lunar arrivals and the importation of such vehicles. It follows that the foundations of selenology will be laid through investigations of local or minor structures, much as geology began on the earth by the examination of layered rocks rather than the study of continents or ice caps. The absence of layered rocks will of course be a detriment to the study of near-surface structures in selenology, but will be more than offset by the absence of erosion, so that deductions as to the origins of structures and the causes of events can be made from relatively complete evidence. In selenology, physical and chemical state will be the important keys to the systematizing of the art rather than depositional sequence. Density and the gravity field will therefore be indispensable tools.

The depositional sequence of lunar materials has been discussed by Shoemaker and Hackman (1960) who suggest that different types of ejecta can be "correlated over most of the visible hemisphere of the moon" and thus built into a lunar time scale. Hackman (1962) has produced a selenological map of the Kepler region, showing surface exposures of various materials identifiable on photographs and by telescopic inspection. The details of structure and the assumption of correlatable layers of material are of course highly conjectural, and in the absence of biological dating evidence the correlation will probably always remain so. Hackman's geologic profiles nevertheless show structures which would undoubtedly give gravity anomalies regardless of the validity of ejecta correlations.

b. Smaller Craters

The most prominent minor structures on the moon are of course the smaller craters. These are generally accepted to be due to the impact of bodies from space, which hit the surface with velocities high enough so that when their kinetic energy is turned to heat it vaporizes them. The heat conversion takes place in a very short while, so that an explosion ensues, scattering the material of the impinging body and pushing the surface material outward from the point of impact. The net result is a central depression surrounded by a raised rim. The theory of impact craters is largely based on the study of terrestrial craters so formed. Not many such craters are known, because they are destroyed in a short time, geologically speaking, by erosion; however, enough of them exist so that a plausible set of hypotheses about their formation has been evolved, and the analogy between them and the lunar craters well established.

The exploration of terrestrial craters by gravity has shown that their interior depressions give large negative anomalies (up to 15 milligals at Deep Bay Labrador, Canada, See Figure 7 for examples) and that their rims give small positive anomalies if there is dense material a short distance below the surface. The positive anomalies are due to the dense material existed a little below the lunar surface would be the positive anomalies in the rims. The negative anomalies are due to the destruction of the rock at the point of impact, so that there is a brecciated zone below the surface. The negative anomaly is an index to the depth of the brecciated zone and thus to the force of the explosion.

A well-known example of a possible impact crater is the Sierra Madera dome in West Texas. (See TI Proposal 101-GD63, NASA). Figure 8 shows the brecciated area in the center and the heavier dolomite and limestone ridge surrounding it. Figure 9 shows gravity, magnetic, and elevation profiles across the crater; the central negative gravity anomaly, and the positive gravity anomaly on the west end of the gravity profile, are conspicuous. The positive anomaly on the east end is less definite, evidently because of a wider distribution of heavy material in that direction.

c. Vulcanism

The possibility that some of the crater-like features of the moon are due to vulcanism rather than to impact is discussed by Shoemaker (1961). In support of this thesis he compares certain lunar craters to the terrestrial features known as maars or maar-type volcanoes. Geologically, maars are subsidence craters with a subsurface vent structure in the center and a ring of ejecta around the rim; the rim, being due to subsidence rather than pressure, is relatively undisturbed. Maars also may have central cones and may exist in alignment with other maars. Shoemaker points out several

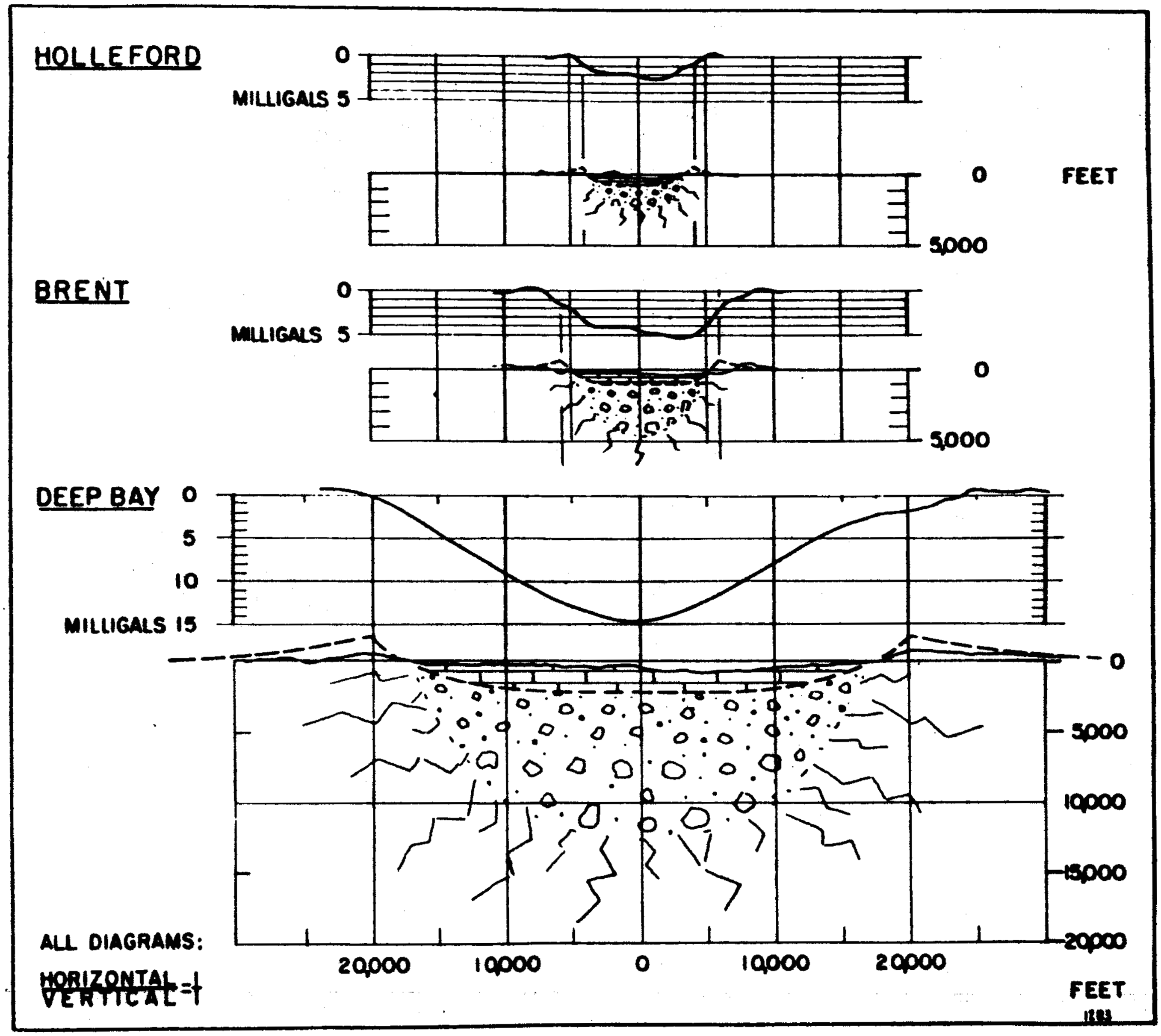

Figure 7. Gravity Anomalies Of Three Impact Craters In Canada (After Innes, 1961)

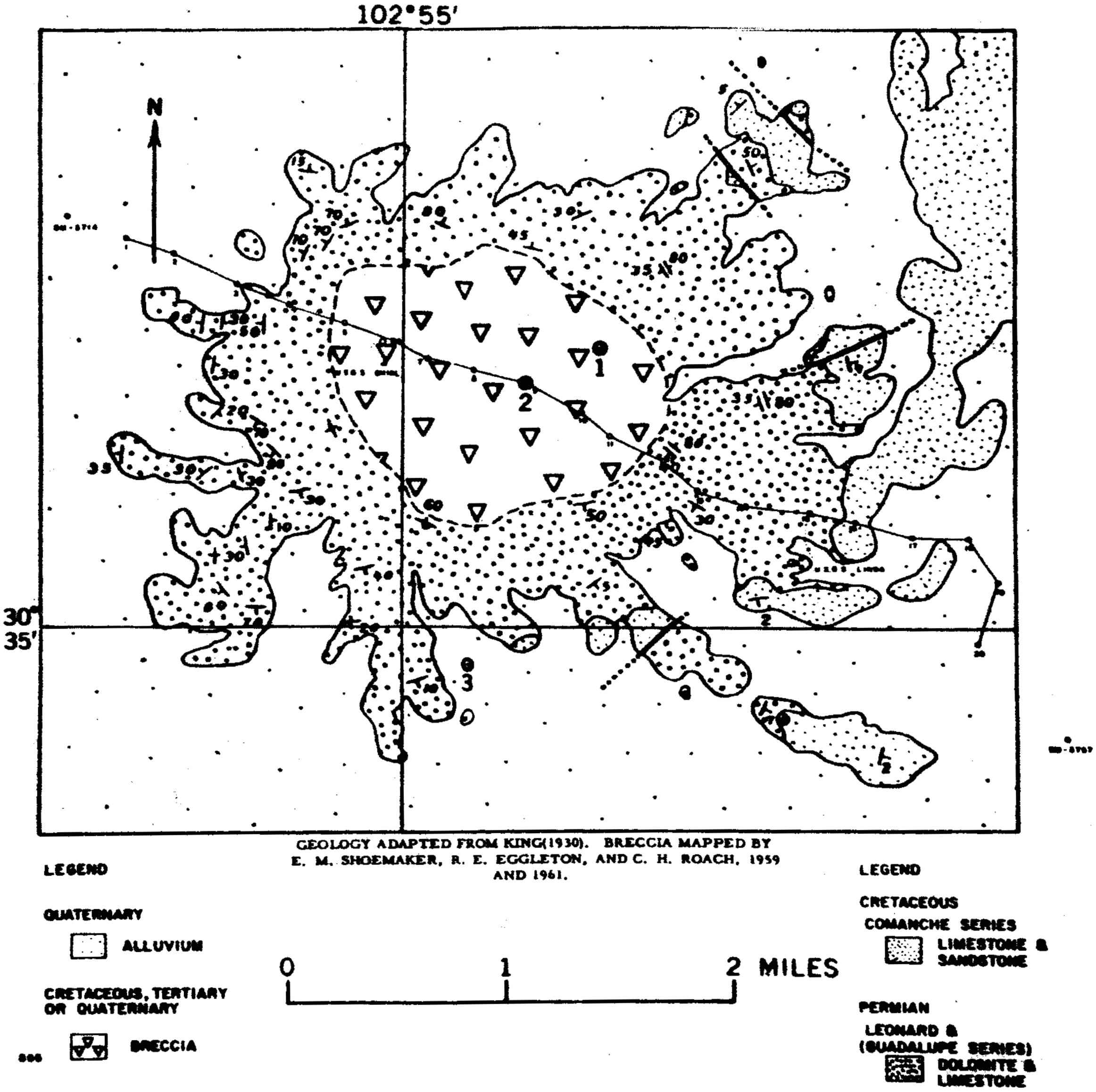

Figure 8. Geology Of The Sierra Madera Dome In West Texas

lunar features that look more like maars than impact craters. He also mentions lunar craters that occur as small holes at the tops of low broad domes, and dome-like features that have no craters at all, as possible volcanic or igneous features. The question of the origin of all such features will probably be quickly answered with the aid of gravity data. The basalt pipes and peripheral intrusions characteristic of terrestrial volcanoes give strong positive anomalies (Figure 10), as do the alignment trends of such volcanoes. Certainly the domes, if as Kopal (1961) suggests they are analogous to laccoliths, will also have strong positive anomalies (unless they are hydro-laccoliths). In general, impact craters should give negative anomalies and volcanic features positive ones.

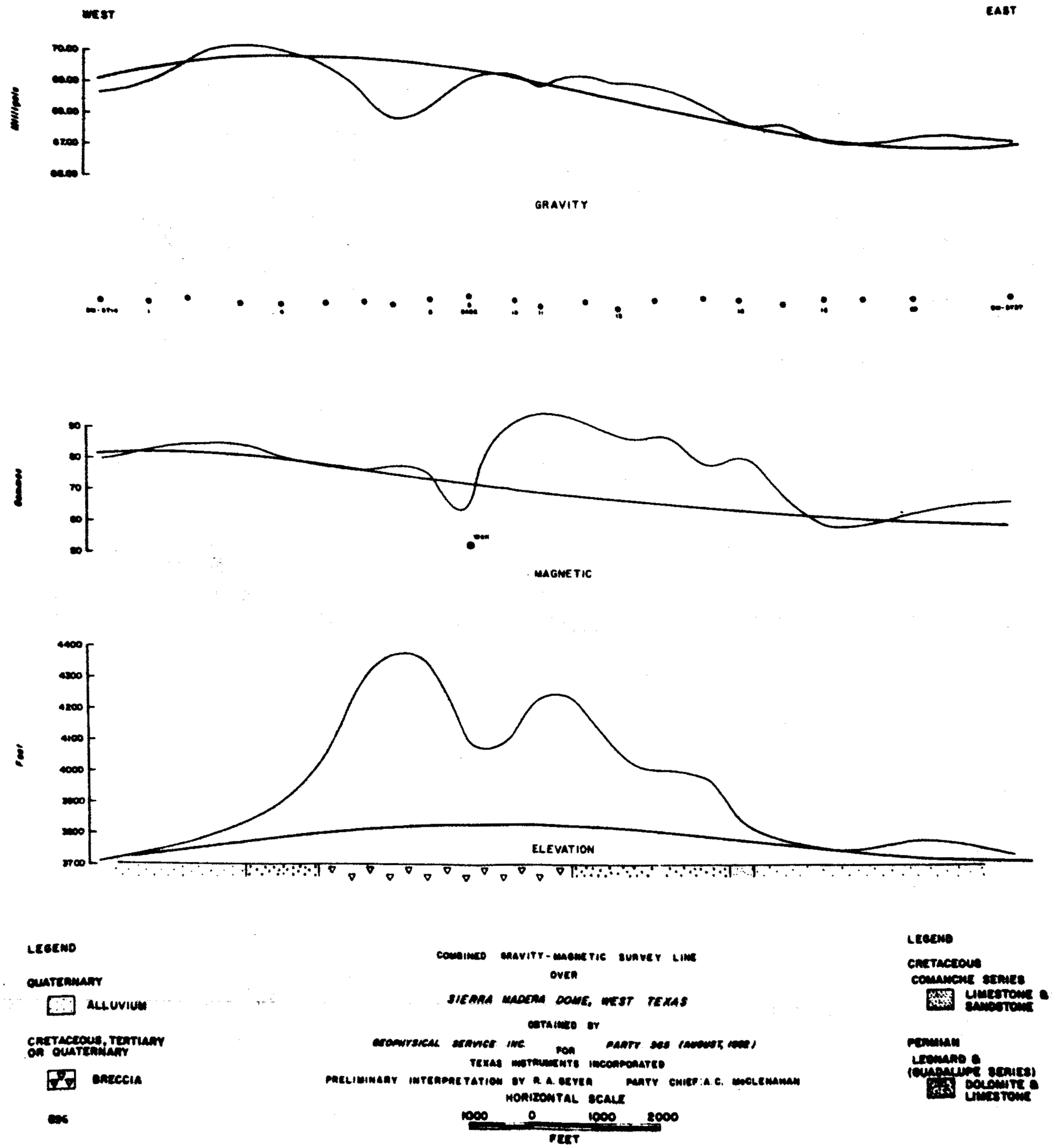

Figure 9. Gravity, Magnetic, And Elevation Profile Over Sierra Madera Dome In West Texas

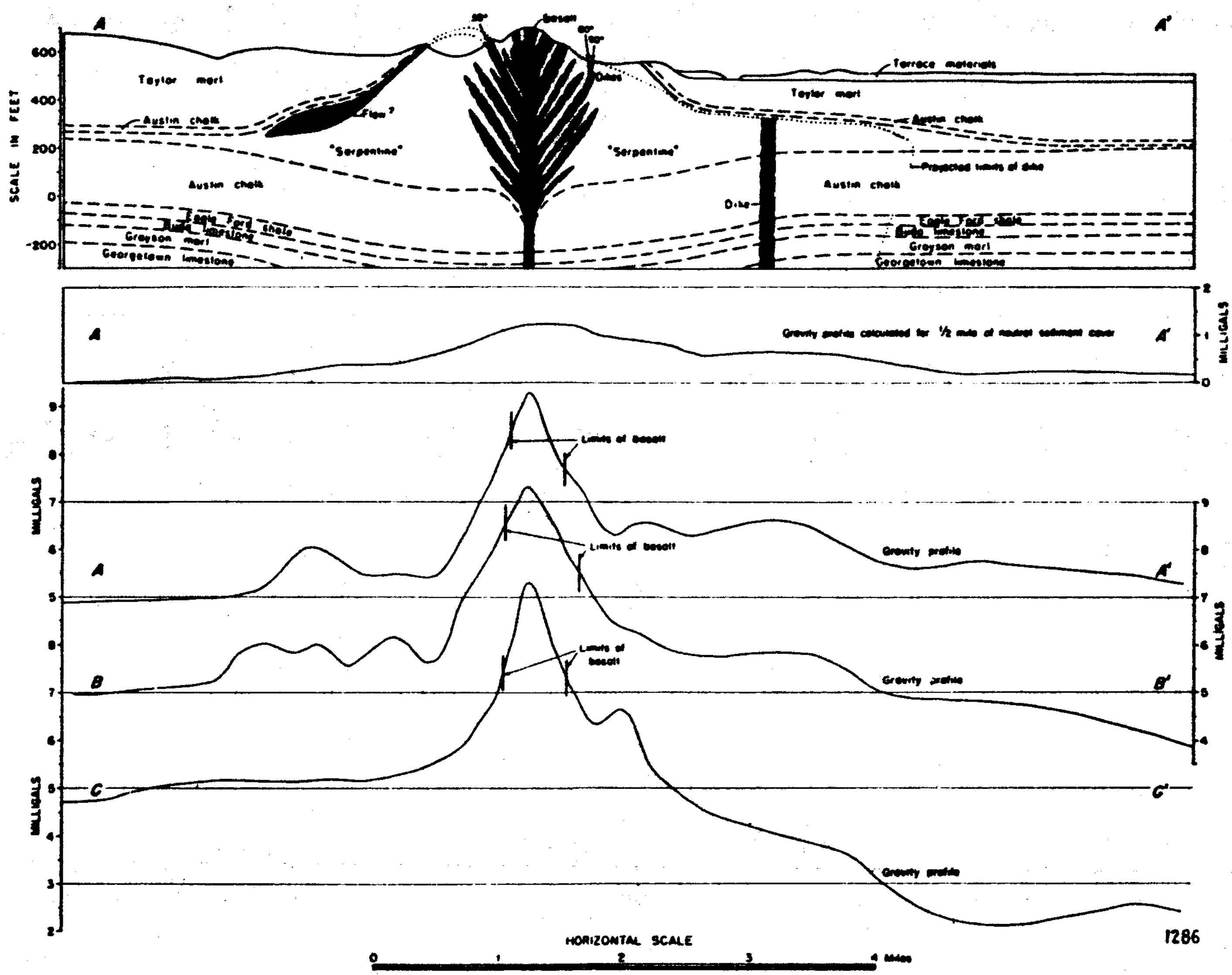

Figure 10. Gravity Anomaly Over An Extinct Volcano, Showing The Anomalies At Main Basalt Stock, A Flow, and A Dike (after Romberg and Barnes, 1954)

One characteristic of vulcanism is the presence of voids such as lava tubes, bubbles, and honeycomb areas. If these are close to the surface they will give negative gravity anomalies. The use of gravity data to find voids has been investigated by theory and experiment, and graphs are available, for instance, showing the relation between volume of cavity, depth of cavity, and amplitude of gravity anomaly. (See Figure 11 and Romberg, 1961b) As would be expected, shallow cavities are easily perceived with gravity measurements, but cavities at depth can be found only if they are fairly large.

d. Rills and Faults

Other minor features amenable to exploration by gravity include rills and faults. Rills are divided by Baldwin (1949, p. 197) into two types, the broad and shallow type and the narrow and deep type. Both, he says, are tension cracks in the lunar crust cutting across other formations, such as craters --- indicating that the craters are older than the rills. Presumably the shallower ones are "more or less completely filled with lava." The surface expression of many possible faults are long and straight, cliff-like structures. Faults give gravity anomalies whose amplitude is proportional to the throw multiplied by the density contrast, and whose sharpness is inversely proportional to the depth. A gravity profile over a lunar fault would be interpreted in terms of the depth and magnitude of the first major density contrast; this would constitute the most specific evidence so far available of a high-density layer in the subsurface. Rills would of course give negative or positive gravity anomalies depending on whether they were empty or full of lava; in the latter case a good estimate of the depth of the resulting dike could be made, assuming of course that the lava is denser than the surface material.

In general, minor geologic features give gravity anomalies and can be partly interpreted with their aid. There are no rules for such interpretation except those which apply to structures of the simplest form. Most problems in the interpretation of gravity are unique. The interpreter must approach each new task - each new observed anomaly - with imagination and an open mind; when he does this he is almost sure to be able to deduce at least one important piece of information about the geologic feature which gives rise to the anomaly.

5. Major Structures

a. The Lunar Crust

When ground vehicles become available on the moon, so that surface exploration on a large scale can begin, the first targets will be the broad features which will have been mapped photogrammetrically from the

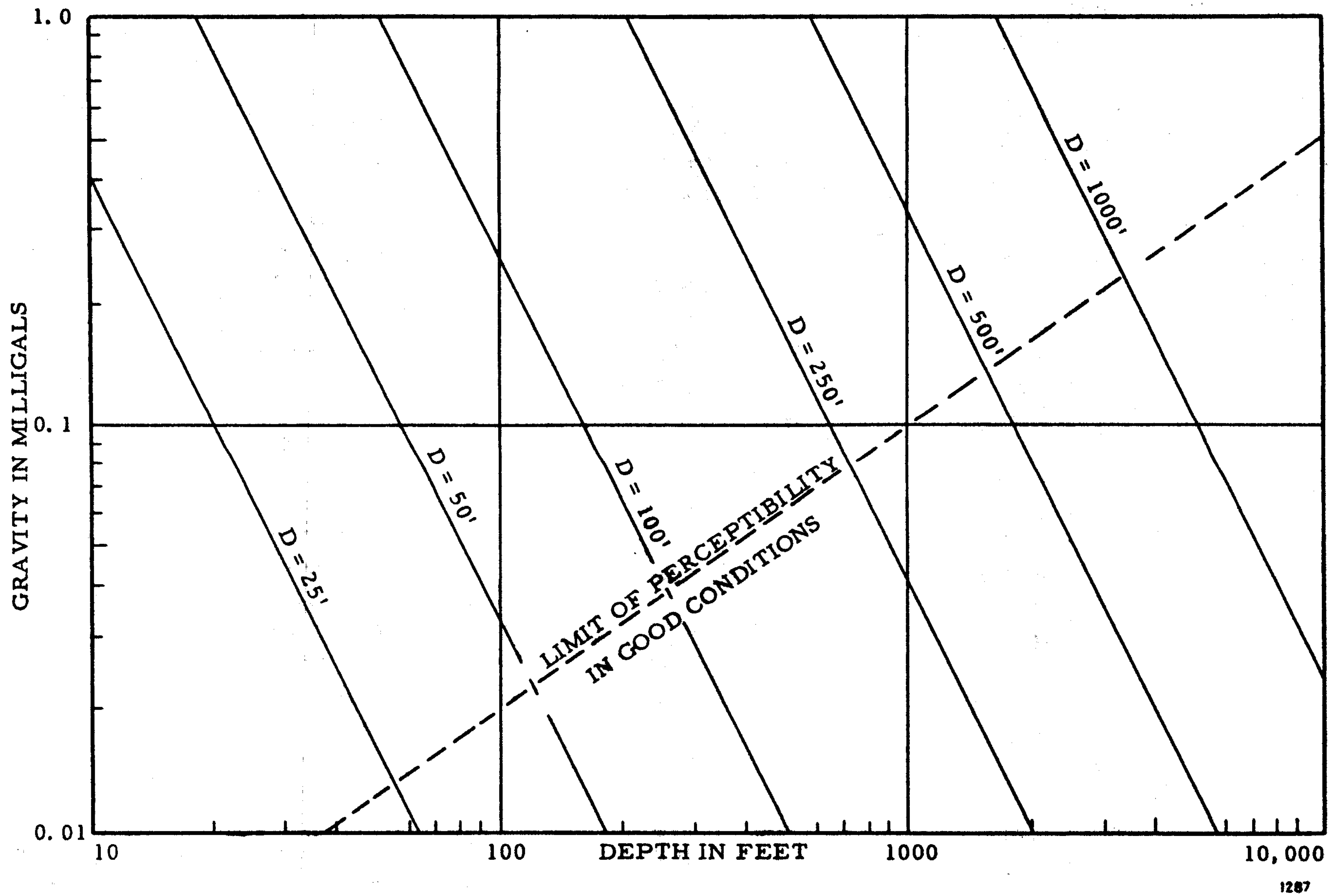

Figure 11. Gravity Anomaly Due To A Spherical Underground Cavity Amplitude vs Depth And Cavity Diameter (after Romberg 1961b)

earth and from orbiting space stations. Until then these will be physically out of reach of astronauts who are afoot. According to Kuiper (1954) the interior of the moon melted at a certain stage, leaving a solid crust only a few kilometers thick that was metamorphosed rather than melted. This crust, he says, should have a density of 2.5, which is different enough from the average density of the moon to cause gravity anomalies of many milligals in places where it does not lie in a layer of uniform thickness. If the Kuiper hypothesis is true, the gravity anomalies will be the key to subsurface selenology and to the origin and substructure of the larger lunar features. For example, the crust will undoubtedly not have the same thickness everywhere, and great regional anomalies in the gravity will be witness to the variations in its depth, just as similar anomalies are evidence and measure of crustal depth on the earth. To go one step into detail, gravity anomalies give a clue to the history and substructure of the mountains. If the mountains are portions of the crust pushed into place by explosions, as presumably are the crater rims, and piled up on an unyielding sub-crust, they will have small Bouguer anomalies. (The Bouguer anomaly is the residual gravity when the visible topography has been accounted for; if a mountain is simply present, with no extra heavy or extra light root structure, its gravity anomaly can be predicted from its contours.) If the mountains were stacked up and then subsided into the sub-crust or lunar mantle, they will have negative Bouguer anomalies in proportion to the amount of subsidence; these anomalies could be many hundreds of milligals for mountains the size of those on the moon. If the older mountains sank into the sub-crust while it was still plastic and the younger ones did not, a significant epoch in lunar history could be dated, at least relatively, by observing which ranges had negative anomalies and which ones did not. Any mountains caused by intrusions, extrusions, or upward folding would, by the same line of reasoning, have positive Bouguer anomalies.

b. Maria

The largest of the major structures are the maria. Baldwin (1949) assumes these are simply lava flows. If this is true it will prove difficult to study them with the methods of surface geology because they are relatively smooth and form an opaque covering over the structure beneath them. The covering, however, is not opaque to gravity nor seismology, though in the case of lava flows seismology is at a disadvantage because the high-velocity layer is above the low-velocity layers. From a practical standpoint, gravity will be the best guide to the substructure of the maria until holes can be drilled through the lava. Their thickness, and the presence of feeders or physical connections with the interior, can be readily deduced from gravity observations. The older structures underneath them can thus be found and outlined. Baldwin (1949, p. 40) says, of the irregular low ridges in the Mare Imbrium, ".... one series in particular is important, for it follows the outline of the inner ring of mountains completely. Quite certainly, under the lava is the raised rim of a vast crater which is very nearly concentric with Mare Imbrium." A set of gravity profiles would promptly confirm (or contradict) this statement, and the ancient mountains or crater rims could be mapped in considerable detail if the lava over their tops is thin.

In examining the differences between the eight great visible maria and the larger craters, Baldwin maintains the hypothesis that while both classes of features are due to impacts, there is a difference in scale and a difference in result - that is, major upwellings of lava. In all the maria, he says, there is evidence of a tremendous subsidence, and in the largest five, he finds evidence of settling or isostatic adjustment after the lavas had hardened. Gravity observations would be a quantitative measure of both faulting and isostatic adjustment.

c. The Larger Craters

The larger craters can be thought of as due to impacts with less disturbing effects than the impacts which caused the maria. The chances are that this is gradational and that the impact which caused a crater of the order of 100 kilometers in diameter penetrated the sub-crust and generally disarranged the attitude of the crust itself. First, the crustal material seems to have been pushed up into big piles around the rim. The relation of these piles with the sub-crust, and how it could be examined with gravity, is discussed under Section (a) above; perhaps the older craters could be differentiated from the newer ones by measuring the roots of their rims. Another detail of interest is the relation of the bowl or inside to crustal structure; did the impinging body go through the crust, or explode in the crust and leave parts of it in place. Of particular interest are the features inside the bowl. Baldwin (1949, p. 32) says of Alpetragius, for example, that it has "... a vast low central mountain, much larger than is normal for such a crater." Apparently there are considerable differences in the intra-crater features; some look as though local melting and temporary volcanic activity occurred, and some have smooth floors as though lava flows had spread out smoothly before solidification. In any case, because of the difference in density between crustal and sub-crustal material, gravity will be the key to the problem.

TASK THREE: GEOPHYSICAL METHODS OTHER THAN GRAVITY

A. INTERDEPENDENCE OF GEOPHYSICAL METHODS

The purpose of Task Three is to examine methods of geophysical exploration other than gravity to see what information about the moon could be obtained from them. In particular we wish to determine whether such information would or would not duplicate that obtained from gravity data. For example, in terrestrial exploration salt domes can be found with either gravity meters or seismographs. On land the cheaper and more efficient method is gravity; at sea it is seismic. In this part of the report we shall search for similar duplications and differences between gravity and other methods.

The most important single fact about geophysical methods is their interdependence. The example of salt domes, which can be found readily by two independent methods, is the exception rather than the rule in exploration targets. Most geophysical methods supplement rather than duplicate each other. Gravity in particular is often said to be meaningless in the absence of geologic or other geophysical knowledge. An observed anomaly tells the interpreter nothing at all that he can translate into geological terms unless he knows what kind of geologic structure to expect in the neighborhood. For instance, a large round negative anomaly in the coastal regions of Texas and Louisiana is almost sure to be a salt dome, but many such anomalies exist elsewhere that are due to entirely different types of structures. For this reason the geophysical interpreter needs all the information available before he postulates the presence of geologic structure.

B. SURVEYING

Surveying is usually not classed as a geophysical technique, but when the whole process of geophysical exploration is considered, surveying is then seen to be not only a necessary concomitant of the other techniques but in one sense the most important of them all. The exploration geophysicist needs first of all to have an accurate three-dimensional map of his prospect. Second, he needs to have through photography as detailed

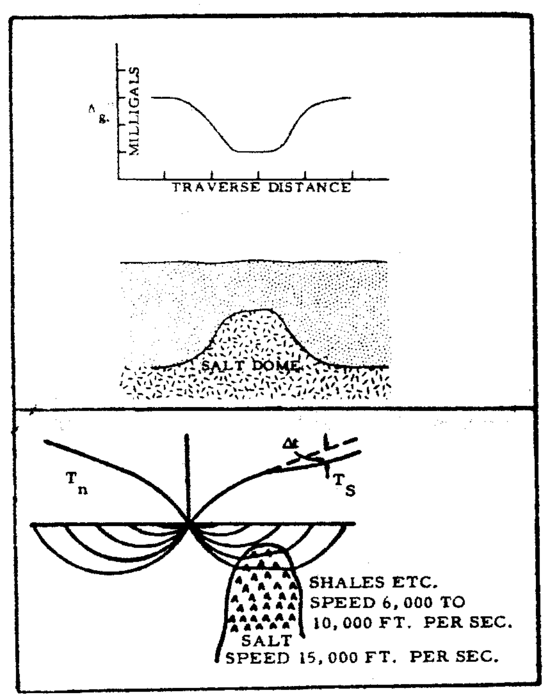

Figure 12. Seismic And Gravity Profiles Of A Salt Dome

a view of the appearance of the prospect as he can get. Topography, on the earth, is what is left of surface structure after erosion; on the moon there is almost nothing of what we call erosion, so topography is the surface structure. It goes without saying that the first subsurface structural knowledge sought on the moon will be in connection with visible structures on the surface.

Figure 13. Surveying With A Tellurometer

The techniques of surveying for geological purposes are well known and there is no need to discuss them at any length in this report. The first step is to make an "aerial" photographic survey; this is being done, in as great detail as is possible, for the visible part of the moon. Doubtless it will be done in much greater detail from orbiting spacecraft before landings are made. The next step is photogrammetric surveying, by which topographic maps are made with the aid of the stereoscopic effect. This type of surveying will also be done from orbiting spacecraft. Lunar orbits are feasible with lower altitude than terrestrial orbits because of the lack of atmosphere, and the velocities are about one-fifth the velocities of lower-altitude earth orbits because of the weaker gravity. No doubt photogrammetric surveying will be accurate enough for interpretation of the longer gravity anomalies, but for the smaller ones, optical and other electromagnetic wave surveying (in the present state of photogrammetry) will probably still be necessary.

Optical surveying and gravity measurements overlap to a certain extent in the mission of determining the figure of the moon, in the same way as they do in determining the figure of the earth. The two methods are not completely equivalent in results, and both will be supplemented to a certain extent by orbiting satellites, used both as camera-carrying vehicles and as sensors for irregularities in the gravity field. It is reasonable to suppose, however, that all three methods will be found necessary.

C. SURFACE GEOLOGY

1. Surface Materials

After surveying, the most important aid to subsurface exploration is to acquire all possible geologic information from the surface itself. The first step in surface geology is to collect samples in order to discover the physical state and chemical composition of the materials available at the surface. As soon as practicable in the course of the exploration program, samples of the surface should be acquired in a systematic way and analyzed in order to deduce all possible information from them. The density, hardness, uniformity, crystalline structure, seismic velocity, electrical resistivity, chemical content and surface distribution of the samples, when measured and tabulated will give the first available evidence of lunar composition and lunar history - matters that to date can only be given by conjecture.

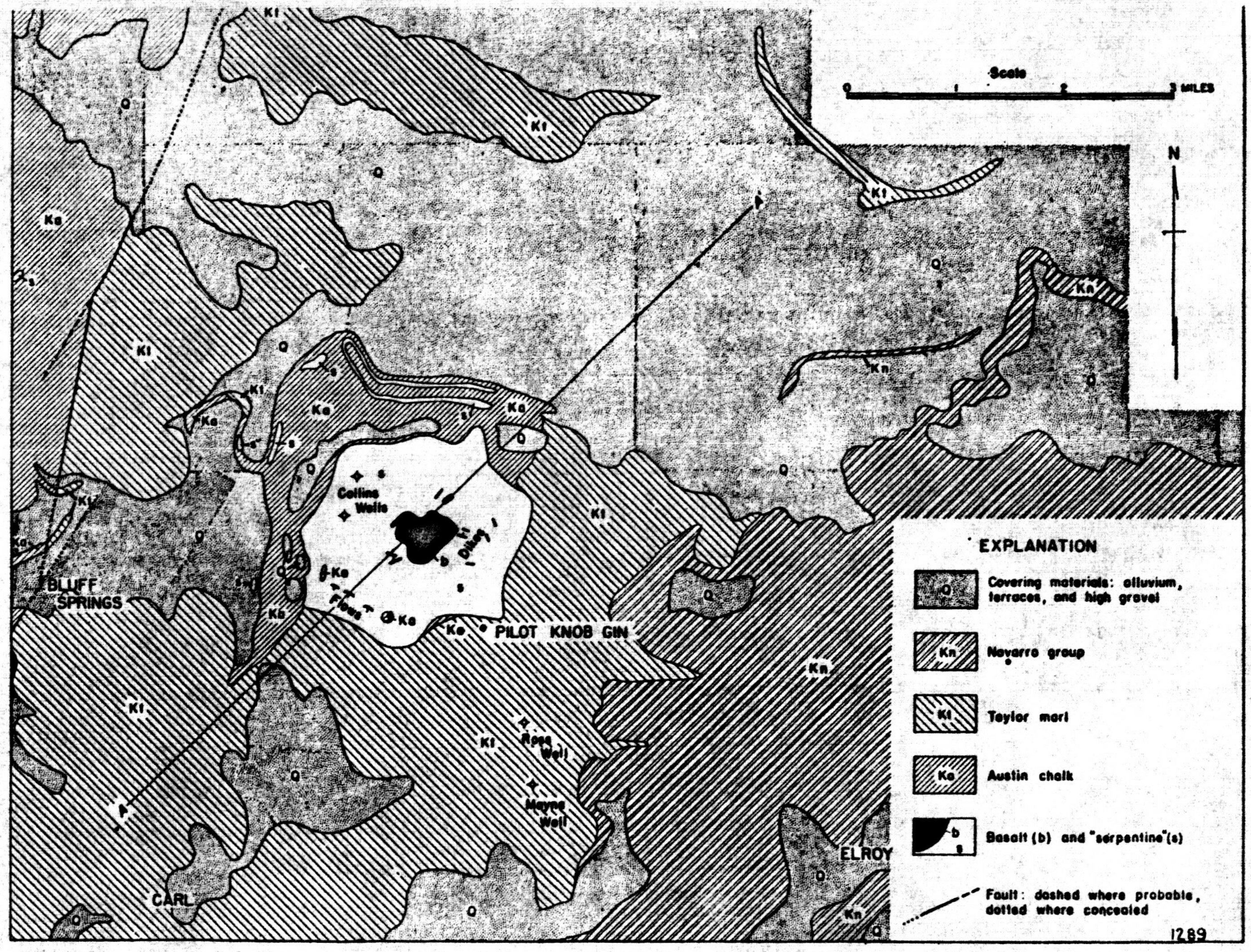

Figure 14. Geologic Map Of An Area In Vicinity Of Pilot Knob (South), Travis Co., Texas (after Romberg and Barnes, 1954)

The information derived from the surface materials bears directly on the use of gravity or any other method in the exploration of the subsurface. The density of surface materials has to be taken into account in the reduction of gravity observations. The variations in density between different kinds of materials are the guide to the discovery of hidden masses of material heavier or lighter than the average of the surroundings. If the distribution of surface materials is found to suggest a pattern, gravity will usually tell whether such a pattern is superficial or deep-seated, by the absence or presence, respectively, of a gravity anomaly.

2. Structure

The basic variable in geophysical exploration is structure. Masses of rock having overall differences in density, composition, and seismic velocity are usually present in shapes or geometric patterns characteristic of their origin or mode of formation. As was shown in the first section of this report, it is assumed that differentiated rock masses in the moon will have shapes and attitudes which will give clues to their origin; this fact holds even if the moon materials were collected mainly by agglomeration and not by geologic processes as understood on the earth.

One great difference exists, however, between the structure of rock masses on the moon and on the earth. Terrestrial structure is dominated, at least in the accessible layers of the crust, by the erosion and solution of water and by the erosion of air. The structure of the visible part of the earth is dominated by stratification of eroded materials, and the accumulation of bodies of minerals is dominated by chemical action. (See White and others, 1963). Air and water, at least as free agents, are probably absent on the moon. Stratification and chemical action will therefore not be the dominant factors on the moon that they are on the earth, and lunar structure will have forms whose shape and distribution we know today only from photographs. It appears from these photographs that not only erosion but strike-slip faulting is absent. The moon's geologic picture, at least on the surface, is therefore different in most of its major aspects from geology on the earth, and it may prove that selenology is indeed different from geology.

Since the geologic agents and therefore the structural patterns on the moon are so very unlike those on the earth, interpretation of geophysical data will necessarily follow new patterns as well. One thing of course will not change. An extra heavy or an extra light mass will give a gravity anomaly. The existence of geologic structure does not guarantee the existence of gravity anomalies; but it is safe to say that if gravity anomalies are observed, structural anomalies are present. It is well known that a gravity anomaly by itself cannot be interpreted uniquely as an anomalous mass of given size and attitude; nevertheless the experienced geophysicist can nearly always make a shrewd guess as to some of the attributes of the anomalous masses that are present. Considering the absence of stratification, moisture, chemical action, and the presumed absence of magnetism, gravity will probably be the key to selenology until the moon is explored by the drill.

3. History

The history of the moon is interesting in itself, but more interesting as a record and possibly a guide to the history of the solar system. The absence of terrestrial geologic agents, discussed in the previous section, has preserved the moon as a record of the action of agents external to it and therefore common to the solar system -- or at least to the inner planets and asteroids. The deduction of lunar history awaits the explanation of present-day lunar features. As was explained in Tasks I and II, the most important subsurface data with respect to these features will probably come from gravity.

D. SEISMOLOGY

1. Near-Surface Structure

Seismology is the most useful guide to structural exploration on the earth. It is in general more effective than the force-field methods of gravity and magnetics because the problem of interpreting seismic data has (within minor uncertainties) a unique solution. The result is that in most mineral exploration, magnetics and gravity are the inexpensive forerunners of seismology, which does a much more definitive job.

The reason for the primacy of seismology as a local exploration method is, of course, the dominance of stratification in geologic structure. Seismology in exploration depends with few exceptions on the existence of discontinuities in the physical characteristics of rocks. If these discontinuities are extensive and persistent, and if they form a surface which is not violently undulatory nor broken into small pieces by faulting, they can be mapped with seismic methods. The contact, for instance, between a limestone and a sandstone member makes an acoustic contrast which will readily reflect impinging seismic energy, and the contact between sedimentary and crystalline basement rock is often mapped with refractions. With minor exceptions seismology is the key to terrestrial exploration of local structure.

It can also be said that within practical limits seismology will be the key to local exploration on the moon wherever suitable discontinuities in the acoustic impedance exist. If rocks exist in strata, as in flat lava flows, or if there are slightly undulating discontinuities, such as that between unconsolidated and crystalline or consolidated materials, seismology will be useful in mapping the discontinuities. It is not yet known how extensively such discontinuities will be found on the moon, but in the absence of erosion we conjecture that they are a minor element in lunar structure. The layers of ejecta postulated by Shoemaker and Hackman are probably not well enough consolidated to conduct seismic energy. Information will be gained about the seismic velocities of the near-surface rocks, and therefore of their physical states, by seismic measurements. It is likely that seismology will be only a fraction as useful for local structure on the moon as it is on the earth.

2. Internal Structure

Seismology furnishes at present the only direct specific evidence of the internal structure of the earth. The discontinuity at the surface of the mantle, the low-velocity zone inside it, the core which does not transmit shear waves, and the inner core, are all features discovered by seismology and described largely by deductions from recordings of earthquake waves which have passed through them. It is reasonable to suppose that seismology will be an equally reliable guide to the internal structure of the moon. Features such as the core and discontinuities (e.g., the Mohorovičić) will undoubtedly be discovered by seismology if they exist. If the natural seismicity is insufficient explosions will be used.

In research on the deep-seated internal structure of the moon, gravity will play a subsidiary rôle only. If discontinuities like the terrestrial mantle-crust interface are discovered, it will probably be found that these are reflected in the surface gravity. The existence of features like the dense inner core affects the total gravity of the moon, and therefore the radial distribution of its mass, but will probably not cause anomalies observable on the surface.

3. Seismicity

Seismicity is evidence of processes that are now in action. Seismicity and the present-day operating forces in the earth are obviously related; zones of active faulting, mountain building, island arc formation, and probably continental drift, are also zones of seismicity. The same thing will of course be true on the moon; any seismicity that is noted will indicate that the focal zone is not in equilibrium; it will be assumed that the processes giving rise to the seismic energy tend to restore an equilibrium that is being slowly distrubed by other processes. The rate at which energy is emitted is a measure of the power exerted by the disturbing force, and the form in which it is transmitted is a guide to the structure of the material in which it takes place.

Large scale seismicity on the earth is usually thought of as being caused by non-volcanic strain release, though major volcanic action always causes earthquakes. Volcanic regions, on the other hand, are a continual source of minor seismicity. If zones of seismicity are discovered, the chances are good that gravity anomalies will be associated with them. (See Barnes and Romberg, 1948, and Romberg and Barnes, 1954). Due to the fact that ordinary gravity meters are sensitive to seismicity, seismic areas will probably be discovered through motion of the gravity-sensing element before a gravity anomaly is noticed.

E. HEAT TRANSFER AND RADIOACTIVITY

Observed thermal gradients, and the rates at which they show heat to be transferred, are a guide to the presence of volcanic action, convective heat transfer, or energy release through radioactivity. They will be useful as evidence of overall lunar history and of local sources of disturbance. The local sources of disturbance may or may not cause perceptible gravity anomalies, depending on what their physical structure is. A natural second step in thermal exploration would be to discover whether an apparent source of heat coincides with an anomalous mass. Conversely, if a gravity anomaly were discovered in a seismic region a heat source would be suspected and a thermal survey would be indicated. The two methods would not overlap to any appreciable extent, since most gravity anomalies would not be thermal sources.

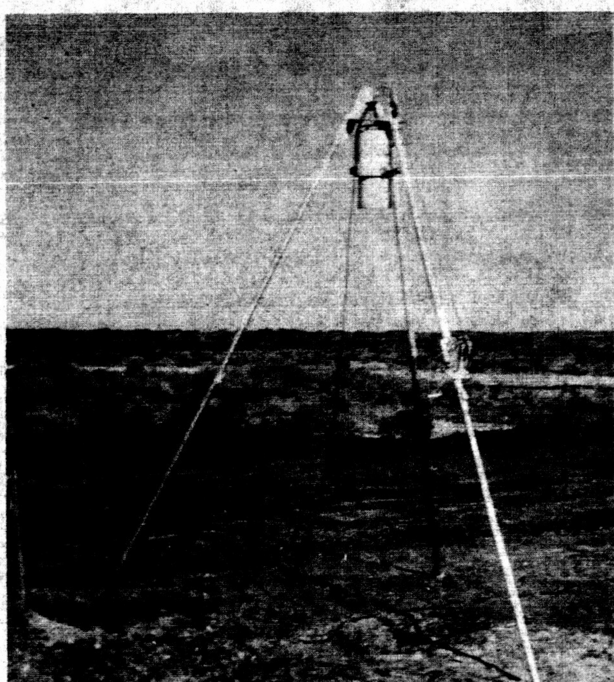

Figure 15. Radioactivity Measurement By A Gamma Ray Spectrometer

Radioactivity as a surface phenomenon is a guide to the presence of radioactive minerals and ores. In terrestrial exploration these usually occur in such a disseminative manner as not to produce gravity anomalies, or at least so as to make exploration for them easier with radioactivity than with gravity. The possibility that the state of affairs is otherwise on the moon ought not to be overlooked, but until different evidence is available it seems improbable that there will be much relation between surface radioactivity and gravity anomalies.

F. ELECTRICAL MEASUREMENTS

Electrical exploration is divided for convenience into active and passive types. The passive electrical method involves sensing electrical phenomena without contributing any energy; the active methods, conversely, involve putting an electrical signal into the earth and observing the response.

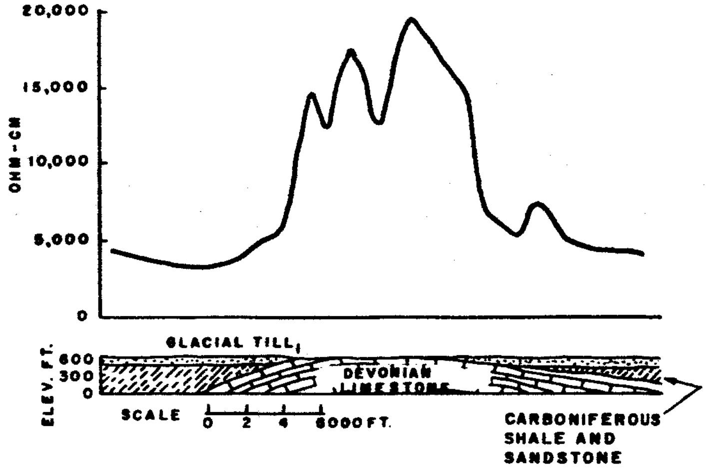

Figure 16. Electrical Resistivity Profile Across Buried Anticline (After Hubbert, 1934)

Passive methods depend obviously on the presence of some natural electromagnetic or electrochemical process which gives rise to potential differences in the earth. One kind of spontaneous potential difference is that due to electrolytic action between metallic substances. According to the picture of the moon accepted as most probable at present, electrolysis will not exist because of the absence of moisture. This suggests that if local voltage differences should be observed they might be clues to the presence of underground dampness. The vacuum and dryness will affect measurements of ground voltage in unpredictable ways in any case, so that the utility of electrical measurements is highly conjectural.

A second class of natural potential difference is that associated with telluric currents. Telluric currents are evidently caused by fluctuations in the magnetic field acting across conducting materials. (Cagniard, 1956). They have been used in terrestrial exploration to map the boundaries between highly resistive and less resistive materials, but their usefulness is marginal in most cases. Since some of the magnetic fluctuations are caused by magnetic storms on the sun, these would cause "telluric" currents, or at least telluric voltages on the moon and could in theory at least be interpreted in terms of sensitivity boundaries, especially deep-seated ones.

Active electrical measurements are strongly affected on the earth by strata with relatively low resistivity; these tend to mask the effects of more highly resistive layers underneath. The theory of resistivity contrasts has been well worked out, but the practice of using them is not as widespread as the development of the theory would indicate it might be. Since there would be no layer of soil or salt water to mask the high-resistivity signals, it is possible that lunar electric exploration would be more effective than it is on earth. Interpretation of electric observations, however, depends for its practicability on the existence of extensive discontinuities, similar in geometry to those required for seismic interpretation, and the efficacy of lunar electrical exploration would depend on the existence of these boundaries.

A discontinuity in the resistivity of rocks is often, though not necessarily, a discontinuity in their density. The active electrical method and the gravity method of exploration will overlap to the extent that such resistivity and density discontinuities correlate with each other. As a guess the resistivity discontinuities present will not in general have a shape suitable for electrical method, due to the characteristic lack of stratification on the moon.

G. MAGNETIC FIELDS

Terrestrial exploration by magnetic methods is easy and effective because of the earth's large magnetic field and the wide variations in the magnetic susceptibility of earth materials. For example, the susceptibilities of sediments are characteristically low, while those of igneous rocks are high. This enables magnetics to be used effectively in mapping the boundaries between igneous and sedimentary rocks. Until recently, the limiting factor in terrestrial magnetic exploration was the so-called magnetic noise, mainly caused by the solar magnetic storms: i.e., the significant fluctuations in the earth's magnetic field caused by geologic structure were fainter than those caused by storms. A newly developed technique, however (see Ward, 1959), uses the noise itself as a signal by observing the difference in its polarization in different locations. If susceptibility contrasts are present, the signals differ in a characteristic way and the presence of a structural anomaly may be deduced.

Magnetic exploration on the moon will probably begin with the technique just described, i.e., using the noise for a signal. It is thought at present that the lunar magnetic field is very weak compared to that of the earth. If this is ture, ordinary magnetometer methods would not be useful, as induced magnetic anomalies are proportional to the inducing field; with a very weak inducing field the anomalies would

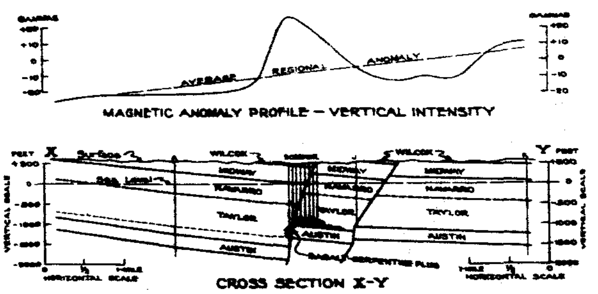

Figure 17. Cross Section And Profile Of Magnetic Vertical Intensity Anomaly (after Collingwood, 1930)

become inperceptible because of overshadowing by noise. Signals from solar magnetic storms, however, will be as strong as they are on the earth, and equally effective in finding susceptibility contrasts.

Magnetic exploration is related to gravity in that susceptibility contrasts often coincide with density contrasts. For the discovery of large ore bodies, the gravity method is as applicable as magnetics in a strong field if the terrain is regular. If the magnetic field is weak, so that external magnetic phenomena must be used for signals, magnetic observations for lunar exploration purposes would probably not be made except in prospecting for ore bodies of economic significance.

H. MECHANICAL

The final stage in any process of subsurface exploration is, of course, the penetration of subsurface rock by mechanical means and the recovery of samples. The purpose of all geophysical exploration is to guide the drill. Since drilling is expensive, it is desirable to confine drilling as far as possible to those locations where the probability of finding the target materials is highest. Thus, mechanical penetration is supplemented by all other methods of exploration, and their value or efficacy is in the long run determined by the quality of samples that are found by drilling. On the moon, of course, any drilling that is done will be informative, but it goes without saying that drilling sites will be selected and culled with utmost care. After topography and surface geology, it seems likely that gravity will be the most important factor in the selection of drilling sites, at lease until much that is now unknown and largely unanticipated is discovered.

Figure 18. Drilling Equipment For Core-Sampling Operations

TASK FOUR: MODES OF OPERATION

A. INFLUENCE OF THE OPERATING MODE

The purpose of Task Four is to show how the operating mode of a gravity-sensing device determines the quality and quantity of the observations that can be made. The operation of a direct gravity sensor is affected, perhaps more than with any other geophysical sensing instrument, by any motion it undergoes while being read. The reason for this is of course that an acceleration sensor cannot distinguish between the acceleration of gravity and the acceleration due to motion. Inherently, therefore, the motion of a vehicle transporting a gravity meter must either be (1) halted for the purpose of making an observation, (2) made so smooth as not to contain accelerations above a specified level, or (3) have its acceleration measured and allowed for in the read-out routine. Clearly the method used to transport a gravity meter restricts the form of instrument that may be used and controls the number, spacing and accuracy of the observations. It follows that the geophysical information that can be obtained, and the geological deductions that can be made from it, are also intimately related to the mode of transportation that is used.

We shall examine the influence of the operating mode on gravity exploration by considering in order the following types of transport: (1) Hard-landing, (2) soft-landing, (3) stationary (manned), (4) roving (unmanned and manned), and (5) hovering.

B. THE HARD LANDING

1. Priority

The first measurements of gravity (or any other phenomenon) taken on the moon will in all probability be made by meters transported in spacecraft designed for hard landings. Hard-landing spacecraft are clearly first in the general lunar exploration program, and the technological gap between these and soft-landing devices is so great that unless we are content to do without gravitational knowledge for a good while, the first measurements of gravity will be made by an instrument devised to withstand a hard landing.

2. Advantages

The advantage of including gravity meters on hard-landing spacecraft is that of enabling basic knowledge about the moon to be gained in the now imminent phase of exploration, without waiting for the development of, and for available space in, a soft-landing device. The present program of lunar study and exploration is a technological feat of such difficulty that it is not possible to predict with confidence when a given stage will be reached.

In addition to the expected technical difficulties there is uncertainty in the rate at which funding for the project will become available. The knowledge of the moon which one or more successful hard landings will bring to light was discussed previously in this report. It may prove that this knowledge is important enough in the early stages of moon exploration -- for guidance as well as for pure information -- as to warrant including several gravity sensors in the hard-landing spacecraft well before soft landings are possible.

A second advantage of including gravity sensors in hard-landing spacecraft is to gain experience with scientific devices for incorporation into the design of the more delicate instruments to be soft-landed later. Aside from the actual shock of landing, environmental hardships such as temperature changes, radiation, and the mechanical state of the surface will be the same for both systems. The soft-landing spacecraft, with its more complicated retro-rocket and guidance system, will necessarily be more expensive than the hard-landing type. The "fare" for transporting something in it will thus be so much the higher. It follows that a device light and rugged enough to travel in a hard-landing spacecraft should be launched as soon as the opportunity offers, so as to provide proven devices for later and costlier spacecraft.

3. <u>Disadvantages</u>

The principal disadvantage of a hard-landing gravity reading from the standpoint of exploration, will be the uncertainty in calibration. Calibration is, however, not the most serious problem. The most serious problem is shock damage. Shock, however, can be provided and over-provided, in terrestrial laboratory tests, so that a meter can be built which has actually survived a greater shock than is expected for a lunar landing. In addition, if the instrument does not survive the landing, the fact will become apparent to whoever is observing it. Calibration for lunar ranges, on the other hand, cannot be easily verified in any accessible laboratory on the earth, so that when the meter reaches the moon its calibration must be inferred. It has been shown that if a hard-landed meter obtained a valid gravity value substantially outside the range of predicted values, the result would give support to Macdonald's thesis that the body of the moon is heterogeneous tangentially and differs in density from one sector to another. Even if erratic results are obtained from the first hard landing, however, the Macdonald hypothesis will still look less probable than the assumption that the calibration has changed. Until manned vehicles are in use, there will always be an uncertainty in calibration.

Other disadvantages of hard-landing operation are that the ruggedness and small size of the sensor will probably make it impossible to read gravity more accurately than to plus or minus four or five milligals. Because of plain physical restrictions, and because of the need to avoid complications, almost nothing in the way of heat capacity or redundant auxiliary devices can be built in.

4. Deceleration

The maximum deceleration to be expected in the present form of hard-landing vehicles is a function of the thickness of the balsa covering with which the capsule is shielded. The balsa is at present some 20 centimeters thick. This means that if the landing surface were unyielding, but the balsa covering behaved in the optimum manner for a particular landing speed, the velocities which gave certain decelerations could be computed. Some examples are given in the table below:

Deceleration	Velocity Meters/sec.	Velocity Feet/sec.
1000 g	63	206
2000 g	89	290
3000 g	110	360

C. THE SOFT LANDING

1. Advantage over Hard-Landing

The next stage of evolution in lunar spacecraft is of course the soft-landing device. The immediate advantage of a soft landing to geophysical equipment is to eliminate (in large part) the restrictions of simplicity and ruggedness which are so drastically in force in the hard-landing spacecraft. A soft-landing gravity meter can naturally be made to read much more accurately than a hard-landing meter. In addition, a set of testing and checking devices can be built into the system which will permit calibration and operational checks. These will greatly increase the confidence which can be given to the readings and therefore the scope of the deductions which can be made from them.

2. Improved Accuracy

A gravity meter carried in a soft-landing vehicle would be no more difficult to build than a terrestrial meter except for the necessary temperature compensation and the inclusion of electronic read-out components that are not affected by radiation. Terrestrial meters can be read with a precision of 0.01 milligal or 10^{-8} g. A lunar meter does not need to be so accurate unles extremely precise readings of the lunar tide are desired, but an accuracy of 10^{-8} g is easily attainable in a meter which does not have to withstand shock. In order to exploit fully the improvement in accuracy it would be necessary to refine greatly the temperature compensation, leveling, read-out system, and the calibration of the present design. However, these things can almost certainly be done within a predictable amount of development cost and time if the requirement to withstand hard-landing shock is removed.

3. Advanced Instrumentation

The soft-landing gravity meter will be an advance over the hard-landing instrument not only because of increased accuracy, but because of features designed to provide confirmation and redundancy in the read-out system. All hard-landing systems are in a sense a gamble; no matter how thoroughly they are tested there is always a chance that the extrapolations necessary to convert to lunar ranges may not be accurate, or the environment not correctly predicted. For instance, if certain theories (see Task I and II) about the moon's composition are true the first two or three gravity readings may be meaningless in terms of the theories now in favor. If, however, an expected value is observed in the case of a hard-landing meter, this will not confirm the less popular theories because of the doubt that will necessarily exist concerning calibration. A soft-landing meter could include either a tilting device or a mass-changing device as a calibrator, and upon interrogation could re-level, or calibrate itself. Any advantages that might accrue through the use of a metal-spring meter could also be exploited.

In addition to permitting more accuracy and elegance in gravity meter design, a soft landing would also permit the oscillating system to be designed with a much longer period or even a variable period. This would permit more effective functioning as a seismograph than the hard-landing, short-period instrument. Long-period seismographs and earth-tide meters have recently provided new information about the earth's elasticity and fundamental modes of vibration as well as about crustal structure. Similar information about the moon could be deduced from measurements made by the same kind of instruments. The threshold of detectable intermediate-period earth energy is relatively high because of the ever-present six-second microseisms. Since these are caused by weather and ocean waves, they do not exist on the moon. Consequently, broad-band seismic reception at the moon should be possible for much lower amplitudes.

The use of a gradiometer in a hard-landing spacecraft was examined (see Task V) and it was concluded that the apparent handicaps to successful gradiometer transport were so great as to discourage their use. The gradiometer, to be diagnostic as a one-location device on the lunar surface, would have to be as delicately calibrated as a terrestrial gravity meter. Gradiometers are not used for terrestrial exploration because gravity meters, being fairly insensitive to transport effects, give the necessary information from three neighboring stations. An accurate gradiometer at a single location, however, would give an extra bit of information about the lunar surface.

D. STATIONARY MANNED SPACECRAFT

1. Assumptions

It is assumed that the next technological development will be a soft-landing, stationary, manned spacecraft. Such a spacecraft will undoubtedly have an egress lock to permit its passenger or passengers to explore the surface. If the surface is firm so that such exploration can be made without any more effort than on a dry bare terrestrial surface, excursions can be made to the limits of communication links and portable life-support systems. On the earthward side of the moon the expeditions would probably be most easily made at night because it is easier to produce heat than to ge rid of it. A space-suit is necessarily air-tight, and no heat would be lost from convection, the most serious cause of heat loss in cold places on the earth. Light would be furnished by the earth. On the moon's opposite side travel at night might be dangerous, since there would be no earth shine for illumination. For daytime travel shoes could be protected against conduction from the ground, but the space suit would have to be shielded from direct, reflected, and re-radiated heat. In any case, it will be assumed that the explorer will be able to carry a gravity meter. Except for sampling and close-up photography, the gravity traverse will probably be the simplest way to get basic information about the materials and structure of the moon's surface. Traverses of several kilometers will be possible even before roving vehicles are available. With the information thus collected, subsurface studies can be made of all the smaller lunar features.

2. Portable Gravity Meter

A gravity meter to be carried by an explorer is the easiest sort to design for lunar operation because it most nearly resembles the instruments now in existence. It should be maintained at a constant temperature to avoid thermal gradients resulting from moving the meter from the vehicle to the outside. This could be done as in terrestrial operation with electrical energy; less will be needed than on earth because of the absence of wind, and the weight of the batteries will not be of any consequence. The chief difference between a lunar portable meter and its terrestrial prototype will be the readout system. It will be highly desirable to balance the beam by reading an indicator needle instead of an optical eyepiece, and to record the reading photographically instead of in a notebook. These techniques are well developed in present-day gravity meters and other instruments and do not merit extensive discussion here.

Calibration of the portable lunar gravity meter can be accomplished in two ways. Either the reference base will be calibrated in a separate instrument, as is now done on earth, or the range of the portable meter will be increased by the addition of an extra mass. The accuracy of the calibration will depend on the accuracy with which its mass and the geometry of the meter are known. By the time manned soft landings are made on the moon the calibration process should be well understood and routine.

3. Leveling Devices

A serious handicap in running gravity traverses on the moon is the difficulty of measuring the elevations of the observation points. A terrestrial gravity observation has significance for the local geology only if it is compared with neighboring observations and the elevation of the spot where it was made is accurately known. As long as the observer remains within sight of the base vehicle, a spacecraft, he can determine his distance and the altitude of his line of sight with an optical instrument. As soon as he loses sight of the base, however, there will be no way for him to place himself or be placed, and this will occur in a shorter distance than it does on the earth. The expedient - inaccurate even on the earth - of using a barometer to measure elevation will not be open to him. No radio-location devices now known will measure elevation to the required accuracy. It will therefore be necessary (pending the invention of such devices) for the gravity observer to conduct optical leveling operations exactly as on the earth. (See Appendix B for details of surveying problems.)

4. Gradiometer Applications

The gradiometer is (to the first order) independent of small changes in elevation, and if an accurate and handy vertical gradiometer is developed, it may well prove that the first selenophysical exploration from manned lunar landing spacecraft ought to be done with a gradiometer. As described in the preceding paragraph, optical leveling is a tedious process. It requires two operators to be done with any dispatch at all, and to place that burden on a lunar explorer may not be advisable -- at least until it is done as part of a full selenodetic program.

The present-day horizontal gradiometer is known as a torsion balance, and has the disadvantage of slow operation. Since the instrument was superseded by the portable gravity meter in the 1930's, no developmental effort has been made to improve the original models. There is no reason to doubt that, if needed, both horizontal and vertical gradiometers could be developed for lunar operation. Much local geologic information can be deduced from readings of the gradient, especially at lesser depths. It therefore seems appropriate to recommend the development of gradiometers for lunar exploration in time to accompany the first manned operations.

E. ROVING VEHICLE

1. Unmanned

An unmanned roving vehicle, called RUM* has been developed for the purpose of sea-bottom exploration. A vehicle similar in purpose would be essential for lunar exploration and would constitute an important milestone in the progress of the exploration program. Such a vehicle would resemble a tractor or a military tank except that it would be very lightly built. It would not require any of the shielding, temperature control, or other complications necessary to preserve human life, and it would be in a sense expendable, though of course the expense of carrying cargo to the moon makes nothing really expendable. The vehicle might be propelled by nuclear energy and guided by radio, and in the absence of an ionosphere the guidance would probably be accomplished by relaying signals from lunar satellites. The function of the vehicle would be to collect samples, to take pictures by ultraviolet visible and infrared light and to record its course in distance, direction, and elevation by an inertial-guidance road log. Such a vehicle would enormously broaden the scope of exploration on the moon.

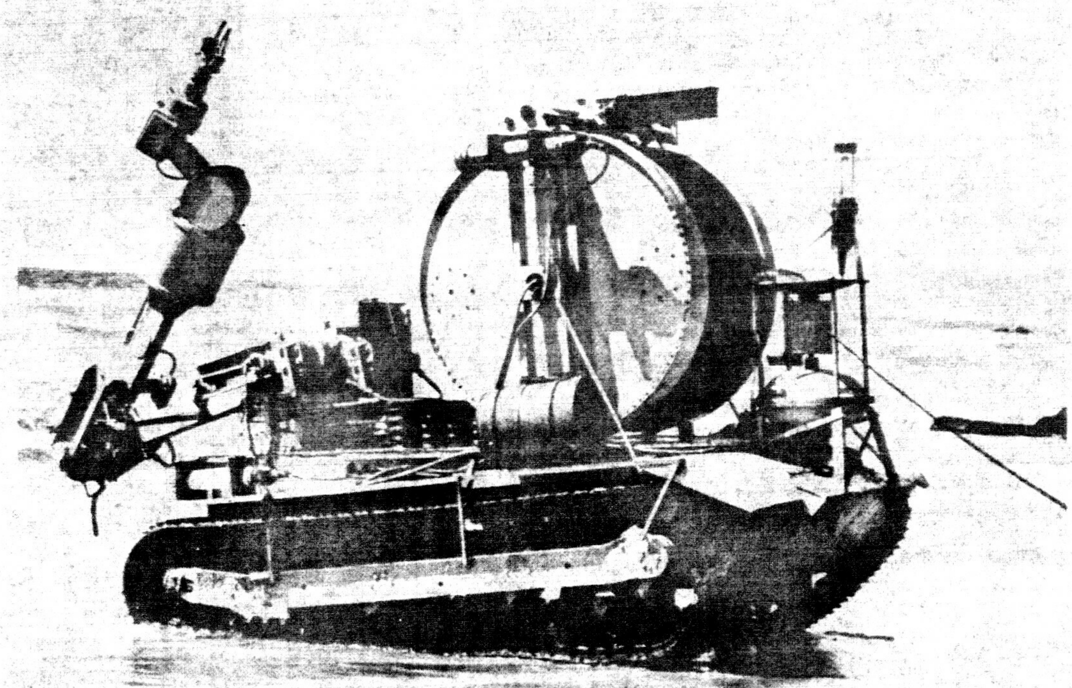

Figure 19. Remote Underwater Manipulator (RUM)
(after Taylor, 1962)

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* Remote Underwater Manipulator

A gravity meter and a gradiometer would be routine equipment on the roving vehicle. Both would be regular land-operation models with the addition of an automatic leveling and reading device which would level the instruments, read them, and record the reading on a command when the vehicle stopped. No surveying would be necessary because of the automatic road log. Other geophysical equipment might be added as special-purpose techniques were developed for the discovery of specific anomalies, but none of the other geophysical methods promise to be so generally and immediately useful. The roving unmanned vehicle would provide the first opportunity in the lunar program for systematic exploration of the type developed for terrestrial use.

2. Manned Vehicle

The manned vehicle is the next natural step in lunar exploration. It would be a much more complicated device than the unmanned vehicle, since it would require shielding and a life-support chamber for the riders. In addition it would need safety devices and redundant control systems in case of accident or breakdown. There would be an automatic log so that the operator would know where he had been; as in the unmanned vehicle this would obviate the need for leveling. Such a vehicle would carry both a gravity meter and gradiometer which would be read automatically whenever the vehicle stopped. The most significant development necessary would be a gravity computer for applying the corrections automatically so that the operator of the vehicle could explore on the spot the anomalies he discovered.

F. HOVERING

1. Development of a Hovering Vehicle

The most promising mode of transportation for quick and efficient exploration of the large areas of the lunar surface is a hovering vehicle. The disadvantages of ground vehicles for extensive coverage observation are obvious even in terrestrial practice; without the airplane such regions as southern Algeria, western Australia, and central Arabia would be only semi-accessible today. It is therefore reasonable to suppose that a hovering rocket-type vehicle will be available for lunar transportation not long after it is needed. By the time a controllable soft-landing moon rocket has been made to work, the hovering vehicle will merely be an adaptation of it; the chief difficulty would be fuel consumption for the longer time spent near the surface.

2. Special Problems in Gravity Measurement

The chief difficulty in measuring gravity in a hovering vehicle is due to the accelerations. Since no gravity sensor can distinguish between different accelerations, the accelerations due to motion must be measured or sensed by some other means and their effects deducted from the readings of the gravity sensor. The problem has been solved for terrestrial operations; but, for lunar application, special devices must be designed for sensing vertical, lateral and angular motion and computing out the effects.

Helicopter operation is of course the simpler of the two solutions; it evades the problem instead of solving it. The only difficulty in terrestrial practice is the air-wash from the rotor blades; if the effects of this become too serious the cable can be lengthened and the vehicle can hover over a spot offset by a short distance from the instruments. This could also be done with a hovering rocket except for the fact that the exhaust from such a rocket is destructive because of temperature and blast effects. If a gravity meter were let down from a rocket it would inevitably be exposed to the exhaust for a short time, and in order to escape damage it would have to be shielded heavily. (Gas jets rather than true rockets may be usable in view of the 1/6th gravity.)

The other solution to the problem is to carry the instrument inside the vehicle and let it be in constant motion. This mode of operation promises an advantage over the analogous methods on earth. Both ships and airplanes undergo considerable motion due to movements of the water and air, and these disturbances would not affect a lunar craft flying over a surface where there is no atmosphere. The motion would undoubtedly be smoother than seaborne or airborne transportation. There would still, however, be accelerations to be accounted for. In a meter swung in gimbals the horizontal accelerations express themselves as changes in the direction of the apparent vertical--that is, as angular accelerations. These angular accelerations are sensed with an inertial device and as long as their period is shorter than that of the inertial device they are effective. Another way of accomplishing the same purpose is to set the gravity meter on a stable table, but at the moment the stable table is not as effective as the pendulum-gimbal system.

The vertical accelerations are more difficult to account for since their direction is the same as that of gravity. In an airplane, large vertical motions are measured by means of the general navigation system, and the smaller ones - bumps - due to air turbulence are sensed by noting the momentary change in atmospheric pressure. The latter system would of course not operate on the moon, but since the cause of the disturbance would be absent the system might not be necessary. A good navigation system would nevertheless be required; the vehicle would probably be tracked by ground systems and, in addition, log its altitude and velocity by means of radar.

TASK FIVE, ANALYSIS OF SYSTEMS FOR MEASURING GRAVITY

A. BASIC PROBLEMS OF GRAVITY SENSING

The purpose of this task is to examine the different methods of measuring gravity on the earth to see which ones are best adapted for development into a lunar gravity meter. We shall consider both proved methods and those that have only been suggested. All such methods can be divided into two classes, i.e., those which measure the strain in an elastic component and those which measure the frequency of an oscillating device. Examples of each class will be discussed in relation to the problem of measuring lunar gravity.

The basic problem in designing a gravity meter is to make it precise enough to provide useful information. Gravity meters for terrestrial use must be read with a precision of 10^{-8} or even 10^{-9} of the total. It is mechanically difficult to build devices, at least portable ones, which can be calibrated accurately enough to meet this requirement and still retain their calibration during field use over the terrestrial range of ambient temperatures. For work on the moon, the accuracy requirement may be at first, considerably relaxed; a meter that measures to within plus or minus 5 milligals, or 3×10^{-5} of the total, would be quite accurate enough for the first two stages of a lunar exploration program. On the other hand, the wide range of temperature variations and mechanical shocks associated with the first lunar landings add practical difficulties which more than make up for the reduction in the accuracy requirements.

To survive usefully a hard landing on the moon, a gravity meter must retain its calibration through a shock which would smash a terrestrial meter and through a temperature range attainable on the earth's surface only by artificial means.

The effect of motion on the meter will not be a problem in the first stages of lunar exploration with gravity, but will become important as soon as roving vehicles are used. Hard-landing spacecraft and first-generation soft-landing devices will presumably come to rest and provide a stable base for gravity measurements. The problem arises when it becomes desirable to measure gravity in a roving vehicle. The accelerations of such a vehicle, either horizontal or vertical, contribute an effect which a gravity meter cannot distinguish from gravity itself; they must be measured or sensed by independent devices and the gravity readings corrected by the processed readings of such devices. Orbiting vehicles are themselves gravity sensors and respond to gravity by changes in trajectory, though a gravity sensor in the vehicle would, of course, register zero. Ground vehicles can stop for gravity readings, though it would be convenient if gravity could be read while they were in motion. Flying or hovering vehicles have large accelerations which must be taken into account.

One method which will not be considered is timing the free fall of an object. This method promises great accuracy (see Preston-Thomas and others, 1960) but will not be included in this report because it seems to require, at least at present, apparatus that is not portable.

B. PROVED METHODS OF GRAVITY SENSING

1. Spring Systems

a. Principles

At present, the spring system is most commonly used in gravity meters. These systems consist of a mass supported by an elastic member in such a way that the system rests in an equilibrium position on the verge of being unstable. A system in this condition is said to be astatic. In an astatic system a small change in the weight of the mass - that is, in the acceleration of gravity - will cause a large change in its position, much larger than would occur if the mass were simply hung by the spring, so that the change is readily observable by optical or electrial means. Variations in gravity can be measured in principle by observing the change in position of the mass. In practice the tension of the elastic member is changed so as to restore the mass to its original position. Since the change in tension is proportional to the change in gravity, the dial regulating the tension can be calibrated in terms of gravity for reading the instrument.

The problem in building a practical gravity meter based on a spring system is to bring the system close enough to instability so its movements will be large, while keeping it stable enough for use as a practical field instrument. An astatic system is necessarily sensitive to changes in dimensions caused by temperature change or mechanical shock, by creep or drift in the tension member, disturbing influences like magnetic fields, seismic motion, or radiation, and errors in leveling. Another consequence of astatizing a system is that its dynamic range is reduced so that it operates in only a portion of the total range. This means that it cannot measure gravity absolutely but only relatively from one point to another unless it is carefully calibrated.

b. The Quartz-Spring System

The quartz-spring system, as used in the WORDEN* gravity meter, (Figure 20), is better adapted for a lunar gravity meter than any other available sensor type. Its fused-quartz construction makes it smaller, lighter, and stronger for its weight than other spring systems, and it contains a proved temperature-compensation device which is unique. Experiments have been performed which indicate that it will resist landing shock and that temperature compensation will extend over the lunar temperature range.

*Trademark of Texas Instruments Incorporated

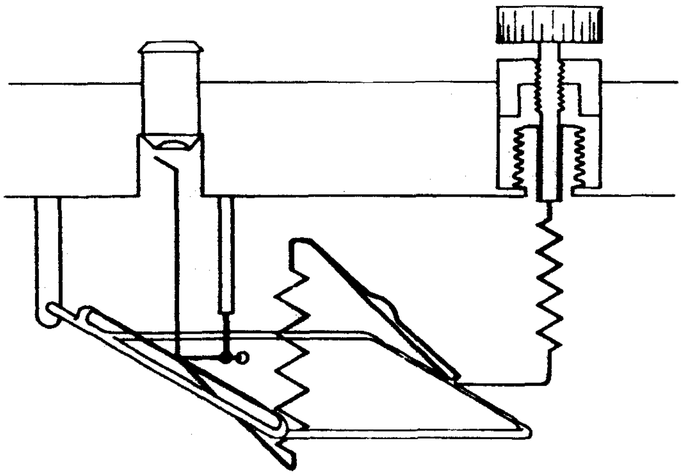

Figure 20. Schematic Of A Quartz Spring Gravity-Sensing Element

The ability of the quartz-spring meter to withstand shock is basically demonstrated by the fact that in terrestrial models its moving system is not furnished with an arrestment. The hinges in an ordinary meter are quartz fibers 0.0002 inches in diameter and 0.01 inches long; these hinges support a gravity-sensitive mass of 0.5 milligrams. It can be shown by experiment that they will support an additional weight of 300 milligrams, or 600 times what is required of them. The hinges of a terrestrial meter should therefore, be capable of supporting an acceleration of 600 times terrestrial gravity. A meter especially built for a shock landing would, of course, have an arrestment and a system of stops to hold its motion within the elastic limit. In addition, the hinges would be made considerably stronger. This would sacrifice accuracy, but since the terrestrial meter is read to a precision of 0.01 milligal, a sacrifice in accuracy of an order of magnitude in a lunar meter would not be significant since the expected error is one milligal or greater.

A preliminary model of the moving system was tested for accelerations up to 1200 g at one millisecond and was not damaged.

The next problem in the development of a lunar gravity meter, second only to that of the landing shock, is range of lunar temperatures. Temperatures on the moon range from $-160^{\circ}C$ at night to over $+100^{\circ}C$ in the daytime, and it is desirable to have a meter that will give accurate readings at both these temperatures. Quartz-spring meters are, at present, unique in that they have been successfully compensated for ordinary temperature changes; all other types of meters require thermostats and good insulation. The compensation device now used in quartz meters does not have sufficient range to compensate for lunar temperatures. Consequently, a different device, or at least one with a greater range, will be required. A special temperature-sensitive resilient quartz component has been built which according to preliminary experiments, is linear enough to be useful through the lunar temperature range.

An additional difficulty with temperature-compensation devices is that when the ambient temperature changes, gradients are set up, so that even if the steady-state compensation were perfect there would still be errors due to the rate of change of temperature. It will not be known until the appropriate experiments are performed how long a time must elapse before a meter subjected to lunar temperature changes reaches a steady temperature. It is obvious, however, that the less massive the meter components are, the more quickly they will reach a uniform temperature after a change. The reason for this is, of course, that heat transfer is proportional to surface area while heat capacity is proportional to mass; the smaller a body is, the greater its surface-to-volume ratio.

The third most important problem in constructing a lunar gravity meter is the calibration. In terrestrial practice the absolute value of gravity is measured with pendulums rather than gravity meters, and even now the best measurement of gravity on the earth contains an error of about 10^{-6} of the total or one milligal. In the design of ordinary gravity meters no attempt is made to give them an absolute calibration; they are used to measure the difference in gravity between one point of observation and another, relying for any determination of absolute value on comparisons with bases where gravity has been determined by other means. This, of course, raises the question of how an instrument for making relative measurements can be used for absolute measurements on the moon, since for a single landing a relative measurement would be useless. The answer is that the gravity meter will be calibrated with respect to a point of known gravity on the earth and will then be used to measure the difference between this point and the point of landing on the moon. The best astatized gravity meters have a dynamic range of 6 or 7 gals (thousands of milligals) but this is insufficient by a factor of more than one hundred to permit them to measure lunar gravity (i.e., 162 gals vs. 980 for the earth). The calibrated dynamic range of the quartz meter can be increased to measure lunar gravity by adding extra mass which will make the instrument read normally on the moon. The mass to be added can be effectively "weighed" only by using it as the mass in a calibrated gravity meter and tilting the meter so as to reduce the effective component of gravity. This can be done successfully because the hinges in a regular meter are strong enough to prevent sag at the required tilt angles, and could be strengthened if it were desired. If m_1 is the regular mass and m_2 the mass to be added, then

$$\frac{m_1}{m_1 + m_2} = \frac{162}{980}$$

which is the ratio of moon gravity to earth gravity. Then if $m_1 + m_2$ is used in a gravity meter calibrated for m_1, the meter will have to be tilted through an angle $\theta = \cos^{-1}(162/980) = \cos^{-1} 0.1653 = 80^\circ\ 29'$. If the meter is to read to five milligals on the moon, the total weight will have to be known (relatively) to one part in 3.2×10^4. If the relative error in the mass is dm, and the angular error is $d\theta$, we have

$$\frac{m}{m_1} = \frac{1}{\cos\theta} \qquad \frac{1}{m_1}\frac{dm}{d\theta} = -\frac{\sin\theta}{\cos^2\theta}$$

$$d\theta = \frac{-dm}{m_1}\frac{\cos^2\theta}{\sin\theta}$$

and $d\theta$ will be 0.4 seconds. To produce a tilt measurable to this accuracy will require procedures similar to those used in calibrating telescope mounts.

Other problems which would appear during the process of building and using a lunar meter are listed and briefly discussed below. It is not expected that these problems would prove as difficult to solve as those of shock, temperature, and calibration.

1) Drift: The rate of drift in quartz gravity meters has been reduced by the use of new techniques in purifying quartz. In the present state of the art, meters which drift less than 0.2 milligals per month can be produced. This is more than sufficient for the purpose.

2) Leveling: An angular error of 15' of arc will produce an error of 1.6 milligals on the moon. A self-leveling gimbal device should level itself with an angular error considerably smaller than 15'.

3) Pressure: Quartz meters are sealed and the internal components do not experience pressure changes.

4) Radiation: Radiation affects the drift rate of quartz meters to a small extent. The solution to the problem is apparently to calibrate typical instruments for exposure to artificial levels of radiation.

5) Magnetic fields: The effect of magnetic fields on the earth is negligible. It is thought that the moon's field is considerably weaker than that of the earth so no problem exists.

6) Read-out signal: The read-out may consist of a low-power lamp, a mirror fused to the rotating system of the sensor, and a pair of silicon photo-sensitive devices to sense the

position of the reflected beam and signal plus, minus, or null. The output voltage of the plus or minus signal causes a motor to turn and operate the nulling mechanism; the motion of the motor is a measure of the change in gravity. Operating systems have been built but they have not been tested for shock and for lunar environment.

7) Seismicity: The sensing element of a normal gravity meter is equivalent to a seismometer with a period of 6 seconds and is hence subject to seismic motion of similar and smaller periods. The system should be critically damped. This is accomplished by retaining sufficient air in the vacuum chamber. The moon meter, not requiring such sensitivity, would probably be a shorter-period device and less subject to seismic motion, which, on earth, has higher amplitude in the longer periods. Gravity meters on earth are subject to seismic motion, but this does not interfere appreciably with their usefulness, and it is not anticipated that lunar seismicity will be greater than terrestrial seismicity.

c. Metal-Spring Systems

The second type of gravity meter in common use is the metal-spring meter, which is fabricated from metal parts. The primary component is an elastic member, usually a spring, made of material with a low thermo-elastic coefficient. The LaCoste-Romberg meter made in the United States, and the Askania meter made in Europe, are probably the best-known of the metal-spring meters.

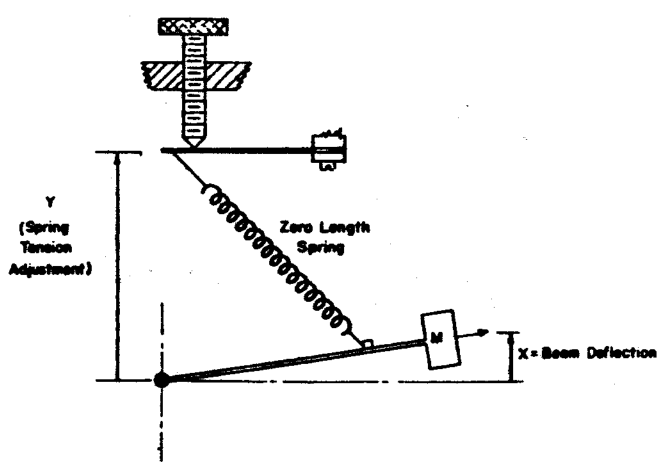

Figure 21. Schematic Of A Metal Spring Gravity-Sensing Element

In the principle, metal-spring meters operate in much the same way as quartz meters; they consist of an astatized system as described in Section a. above. They differ from quartz systems in that they contain many parts that are fastened rather than fused together, their masses weigh many grams instead of milligrams, and they are not easily compensated for temperature. This means that they usually have thermostats, which require power. On the other hand, their reading errors and their drifts are somewhat less than those of other smaller meters, and they have been adapted in the last decade for use in moving vehicles such as submarines, ships, and airplanes. Historically, this adaptation came about through the development of a meter to be read on the ocean bottom. It was found that an underwater meter set on a muddy bottom might undergo a periodic motion (if there were swells in the sea) of several millimeters in amplitude. Such motion caused the beam to bounce against the stops and invalidate the reading. A remedy was to build an elevating screw for the meter housing. When the beam approached the limit of its range, one way or the other, a servo-mechanism turned the elevating screw to move the frame away from the beam. The true reading of gravity was derived from an averaging device. From this beginning, gravity meters have been developed which are capable of being read in vehicles whose irregularities in motion are meters instead of millimeters in amplitude.

The metal-spring meter does not seem, on the whole, to be as adaptable to a hard-landing lunar gravity meter as the quartz-spring meter. The chief reason for this, in the present state of knowledge, is probably its susceptibility to shock damage. Metal-spring meters are tested for their ability to withstand the shocks of terrestrial transport, including accidents, but no tests have been reported involving shocks of the order of hundreds of times gravity. This does not indicate that a metal-spring meter could not be made to withstand such shocks, but it does show that in order to prove the contrary, a course of development and a set of experiments would have to occur, duplicating in part, what has already been done with the quartz-spring meter.

Another major reason why the metal-spring meter is not the best type to consider for a first hard-landing is its susceptibility to temperature change effects. To date, a temperature-compensating device has not been made which is effective enough to eliminate the requirements for thermostats. While a lunar meter could be equipped with a thermostat, at least for a while, it would require either power or a thaw-freeze, heat-sink device that would add weight. In addition, a developmental program would have to be conducted. One advantage of a constant-temperature meter is that the drift problem is reduced considerably.

Calibration of a metal-spring meter would be relatively simple. The present model Askania meter can be adjusted in range by automatic addition of small weights; the process is easier than for a quartz meter because of the relatively great weight of the main mass. The required additive weight could be measured to sufficient accuracy by simple weighing, and the amount required could be determined from the system geometry.

Magnetism is a problem in terrestrial metal-spring meters because the known iso-elastic spring materials are somewhat magnetic.

Unless carefully demagnetized, metal-spring meters may vary several tenths milligal in different orientations of the earth's field. The importance of this problem will depend on the lunar field; it is not anticipated that the moon has enough magnetism to cause an effect, even if the spring became magnetized by induction from the space field.

While spring-system meters do not, for the above reasons, look especially promising for hard-landing vehicles, there is a chance that their freedom from drift, their adaptability to use in a moving vehicle, and their accuracy might make them useful in later stages of lunar exploration. For instance, a tide-recording meter that reads in microgals (10^{-9} gal) (Figure 4) is now on the market for terrestrial use; an instrument of this kind would be highly effective for scientific purposes if it could be soft-landed with enough power to keep it going for two or three revoluations of the moon. For another example, once a hovering vehicle for lunar exploration is developed it should carry a gravity meter of the type now used in airplanes. Such a vehicle is perhaps two "generations" of spacecraft in the future because of the moon's lack of atmosphere, but since lunar gravity is so much less than earth gravity such a vehicle should become available when needed. Meters for use in vehicles need either a stable platform or a set of acceleration sensors for dealing with unwanted motion. Acceleration sensors now available can handle motion with periods of over one minute and are less bulky than stable platforms.

In conclusion it can be said of spring systems that the quartz-spring meter is almost certainly best adapted to a first landing. On the other hand, metal-spring meters now developed have features that would be useful in the later stages of lunar exploration.

2. Pendulums

The simplest method of measuring the acceleration of gravity is to observe the period of oscillation of a pendulum. A pendulum has the advantage over a spring system that it does not need to be astatized to serve as an instrument for measuring gravity. In practice, a simple pendulum of the kind used in clocks is an effective gravity meter; gravity may be determined by setting it into oscillation and measuring its period, without the need for elaborate calibration techniques. Accuracy can be achieved simply by observing a great many periods. An electronic signal indicating the passage of the pendulum through a light beam would be the simplest of all signals to send and decode. These advantages suggest that a pendulum might be the most desirable form for the first lunar gravity meter, especially since simplicity is so important in a device which is to operate after serious transportation shocks in an environment where it cannot possibly be adjusted or repaired.

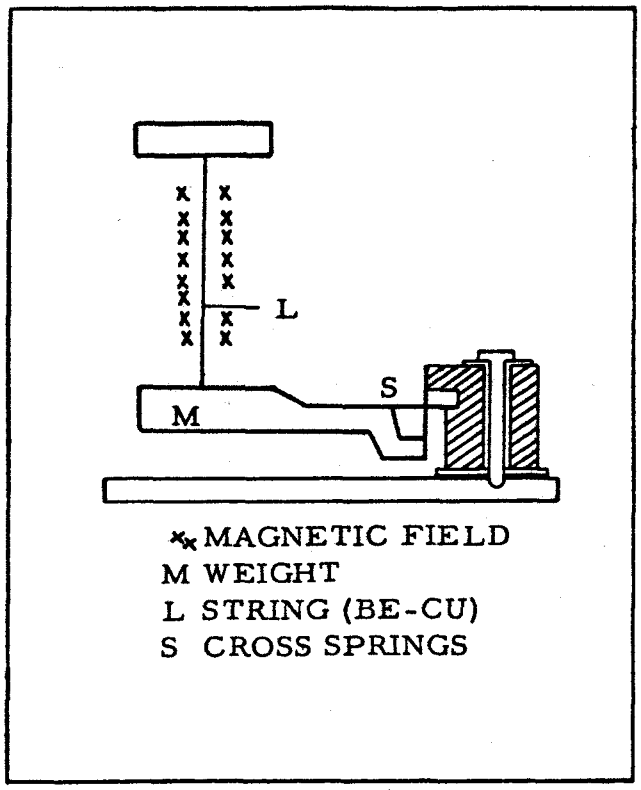

Figure 22. Schematic Of A Vibrating String Gravity-Sensing Element

Further examination of the problem shows, however, that the advantages in simplicity are offset by the disadvantage of low accuracy. In long practice it has been found impossible to determine terrestrial gravity with a smaller probable error than $\pm 10^{-6}$ times the total, even with the most carefully built and elaborately calibrated multiple pendulum systems. Even now the reasons why pendulum determinations of gravity are not more reliable are not well understood. Various causes for instability in the instrument have been suggested but none of the suggested corrections have resulted in significant improvement.

The chief reason for inaccuracy in pendulum measurements of gravity is the uncertainty or instability in the effective working length of the pendulum. The length is the distance from the hinge or pivot point to the center of gravity of the moving mass, but if the mass changes its length because of temperature change or change in effective position of the hinge an error will obviously result. The seriousness of this is to be seen in the elementary theory of pendulum motion. The well-known formula

$$g = \frac{4\pi^2 \ell}{t^2}$$

where g = acceleration of gravity
ℓ = length of the pendulum
t = period of the pendulum

shows the effect of small errors in ℓ and t; the easiest way to demonstrate the effects is to take the partial differentials and divide by the original formula. Thus if the operator Δ signifies "a small error in" we have

$$\frac{\Delta g}{g} = \frac{\Delta \ell}{\ell}$$

for the fractional error caused by an error in length, and

$$\frac{\Delta g}{g} = \frac{-2\Delta t}{t}$$

for that caused by an error in measuring the period. If on the moon we wish to measure gravity to one milligal ($\Delta g/g = 0.6 \times 10^{-5}$) we must measure ℓ with an equal accuracy. Then if the pendulum is 10 centimeters long, we must know the effective length to 0.6×10^{-4} centimeters or less than one micron. The period of such a pendulum on the moon would be about 1.5 seconds, so that the same accuracy requirement would call for a timing error of

$$\Delta t = -t \frac{\Delta g}{2g} = 0.5 \times 10^{-5} \text{ sec}$$

which is easily obtainable.

The principal source of error in practice will thus apparently be the length of the pendulum rather than the timing device. If the pendulum is made of quartz then its variation with temperature can be accurately predicted, so that the chief uncertainties will be the accuracy of leveling, and the effective position of the hinge point. The leveling affects the length in proportion to $1 - \cos\theta$ where θ is the leveling error in the plane perpendicular to the plane of oscillation, so that the leveling would have to be accurate to about 13 minutes of arc, not a stringent requirement.

It seems likely that the hinge effect would constitute the most serious problem. Present-day pendulums are made with hard knife-edge hinges, which pivot on a flat surface. It might be better if the pendulum hinges were not true hinges at all but were made of fused quartz integral with the frame and the pendulum. In this case the hinge point or effective length would undoubtedly change with amplitude but might remain constant (since quartz has very little hysteresis) for a given amplitude. The magnitude of this effect could be calibrated by terrestrial experiments. It would require knowledge of the amplitude of the pendulum motion, but this could be determined by reading the time of passage of the beam at a position offset from the equilibrium position. The amplitude could then be computed from the difference in the observed intervals between passages.

In any case, it is desirable to read the amplitude of the beam. The exact equation of motion of the pendulum is

$$\frac{d^2 \theta}{dt^2} + \frac{g}{l} \sin \theta = 0$$

which is non-linear. For practical purposes it is sufficient to assume that the oscillations are small and the approximation $\theta = \sin \theta$ is good enough. A lunar gravity meter - at least the first one - would have a short pendulum which would swing at an appreciable angle, so that the amplitude would have to be known in order to solve the exact differential equation for g.

A mechanism would have to be provided to give the pendulum a periodic impulse in order to keep it swinging. The impulse would have to be timed so that it would deliver the impulse at exactly the right moment or it would affect the period. This objective could presumably be obtained with a feedback device by the pendulum itself.

A pendulum or an array of pendulums as might be required for lunar gravity measurements, can be constructed from fused quartz much in the same manner as gravity meters, and all of the advantages which are present in quartz gravity meters would accrue to such pendulums. The usual advantages are:

1) small size
2) light weight
3) extreme ruggedness
4) ease in construction
5) versatility in adjustments
6) perfect elasticity

The probable size of a contained housing for one or several pendulums would be about six cubic inches and would weigh, exclusive of read-out electrical components, about 6 or 8 ounces.

Quartz pendulums can be made with the frictionless, torqueless hinge suspension used to suspend the gravity-sensitive mass of a quartz gravity meter. Such a simulated system has already been constructed and shock tested as described in Appendix C. These test models were subjected to 1200 g at 1 millisecond with no failures.

For horizontal or inverted pendulums, the techniques used in construction are highly suitable, since easily adjustable torsion hinges exerting useful torque can be used as required. Experimental instruments built by Texas Instruments personnel have used the bi-stable inverted pendulum as a leveling indicator with marked success.

Signal output from quartz mechanism is no problem, since the technique for integrating optical and electrical components into a quartz system has been perfected.

3. Vibrating String Meters

The vibrating-string gravity meter is similar to the pendulum in that it measures gravity by observing its effect on the period of an oscillating system rather than on the strain in an elastic member. This method reduces to second order the effects of temperature and creep on the elastic member, and avoids the necessity for a mounting that is stable in space. A vibrating-string gravity meter for use in a submarine was built by Gilbert (1949) and meters for use in ships were described by Lozinskaya (1959) and Tsuboi (1961). These instruments in their modern form appear to be accurate to two or three milligals even on shipboard, so that they can be regarded as proved, state-of-the-art instruments, accurate enough for lunar purposes.

The principle of measuring gravity with a vibrating string is expressed in the equation

$$T = 2\ell\sqrt{\frac{m}{Mg}}$$

where T is the period, ℓ the length of the string, m its mass per unit length, and M the mass used to produce the tension Mg as it is supported by the string. In theory the string is inextensible and perfectly flexible, and the tension is constant. The errors in the method are due to small deviations from these assumptions. Unlike the spring-system meters, the vibrating-string meter gives an answer in absolute rather than relative gravity, so that (except for the sources of error noted) the accuracy of the result depends on the accuracy with which the quantities in the above equation can be measured.

In practice the vibrating-string meter consists of a cup-shaped mass suspended by a metal ribbon in an edgewise magnetic field. The cup-shape is to provide eddy-current damping in all directions against pendulous oscillation. (Tsuboi uses horizontal ligatures.) The ribbon, whose length is a few centimeters, is beryllium copper or beryllium bronze; the ribbon-shape is to provide for more flexibility per unit of strength. The wire is made to oscillate in the magnetic field by small surges of current timed by a feed-back device, and the oscillations have a frequency of 1-2000 cps. On the moon the frequencies would be lower, but could be increased by using a longer mass or a shorter or lighter wire. The wire should have a Q of 20-25,000 to avoid being driven by the amplifier. The frequency is determined by comparison with a standard; a lunar meter would simply send out the signal and its frequency would be determined when it was received on earth.

The vibrating-string meter should not be sensitive to shock. If the mass is properly damped for transportation the only thing that could happen to the system would be the breaking of the ribbon from its own inertia; this does not seem a danger. The chief sensitivity to shock would probably be due to the damping mechanism and the electronic system, though this would be simpler than in most lunar meters because it would not include a light-sensing system for displacement or beam interruption, nor mechanical power for anything except a one-time freeing of the weight.

Temperature is an important factor because the length of the suspension varies with temperature and this is one of the major variables. However, if the temperature of the instrument is known (as it should be) the calibration can be corrected accordingly. This would require test operation at actual lunar temperatures, which could of course be done during the environmental tests.

Errors in terrestrial operation are caused by creep, corrosion, pressure leaks, etc. Creep is a serious problem. It can be largely solved by heat-treatment of the materials and by keeping the ribbon under tension even where the main mass was damped. This would present an experimental problem but should be soluble with proper construction. Changes in pressure cause errors by buoying the mass and damping the string. This can be corrected by evacuating the case. Leveling has the straight ($1-\cos\theta$) effect and should be no problem. Magnetic fields would have no effect. Seismic activity might cause the weight to move as a pendulum, but since its period as a pendulum would be less than a second the effective seismic noise would have too small an amplitude to cause trouble. Radiation might affect the electronic parts, although probably less seriously than in instruments with more elaborate electronic systems.

The above analysis seems to lead to the conclusion that a vibrating-string gravity meter for a first flight to the moon would be easy to build. It is also true, however, that since 1949 serious efforts have been made to build vibrating-string meters for use in ships and in bore holes. The former effort was long but it seems to have attained its goal of accuracy of the order of 2 milligals. The bore hole meter, for which one-tenth milligal was needed, does not seem to be forthcoming. For this reason success in building a string gravity meter beyond the present state of the art cannot be predicted, at least if the task must be accomplished in a relatively short time such as twelve or eighteen months.

C. NEW SYSTEMS

1. Piezo-Resistance

Piezo-resistant elements have been used successfully as acceleration sensors for both large and small accelerations. A proposal to design and build an accelerometer for the range 10^{-6} to 10^{-4} g, with an accuracy of $\pm 3 \times 10^{-8}$ g, or one-thirtieth milligal, has been submitted to NASA*. The scientific principles and technical details of the piezo-resistance accelerometer are discussed in this proposal and the part of it relating to the subject are included with this report as Appendix C. Enough experimental work has been done to prove the method feasible but environmental testing and design adaptation to hostile environment is at present in an early stage.

The apparent advantages of a piezo-resistance gravity meter as a hard-landing device are great. Since the only moving part is the strain member itself, the frame can be designed to stop its motion just outside of the expected range and therefore well within the breaking strain. The electrical components will of course be subject to shock but will be rather less vulnerable than the type of components (for example, photo-sensitive devices) necessary for other types of meters. Shock should therefore be a minor problem rather than a major one.

Experiments with piezo-resistant elements as gravity sensors have utilized masses supported for normal gravity by stiff springs and attached to the frame by piezo-resistant members. These members, having very little resilience, are stressed when gravity is more or less than normal by the increased or decreased weight of the mass. They are used in a matched-component push-pull configuration as members of a bridge, so that temperature and other instabilities cancel, and the change in their resistance is a measure of the change in gravity. In its present form the system would be suitable for use as a terrestrial gravity meter, and would have the advantages of not being an astatized system. In addition, it would in effect be a system with no moving parts in the ordinary sense. The only motion that takes place is the microscopic strain on the elements themselves. The effects caused by accelerations attendant on vehicle transport (whether rolling, floating or flying), while they would have to be removed by integration and other correction, would not affect the ability of the instrument to give a correct reading at any moment. This fact makes the design unique.

To adapt the system to a lunar gravity meter would require considerable development. The present design is not adapted to withstand serious shocks; it would either have to be very carefully stopped and clamped or else redesigned for stronger piezo-resistant members, which would entail a read-out problem. The temperature coefficient of piezo-resistance is

*Apparatus Division, Texas Instruments, Proposal No. A-63-93, 19 April 1963 large; while it can be compensated to a certain extent by opposing elements, the possibility of this has not been examined experimentally for the extreme temperatures that are expected. Opposing components in the bridge circuit must be carefully matched, and it is not known how well the matching will withstand environmental changes. The drift is not known. The calibration could be accomplished by adding a suitable weight, as in the Askania metal-spring meter. Other environmental effects would have to be determined by tests.

The conclusion is that while the piezo-resistance gravity meter promises important advantages over other types, certain obvious disadvantages indicate that it is at present less promising than other devices (such as the pendulum and the quartz-spring meter) as a feasible lunar gravity meter.

2. Piezo-Electric

It has been shown that AT-cut quartz oscillator crystals exhibit a frequency sensitivity to radial forces*. The maximum effect occurs when the force is applied along the x axis of the crystal, and for a typical AT-cut crystal amounts to about 17 parts per million per newton.

Figure 23 is a schematic representation of a gravity meter using this principle. Two matched crystals are used to help compensate for drifts from temperature and aging.

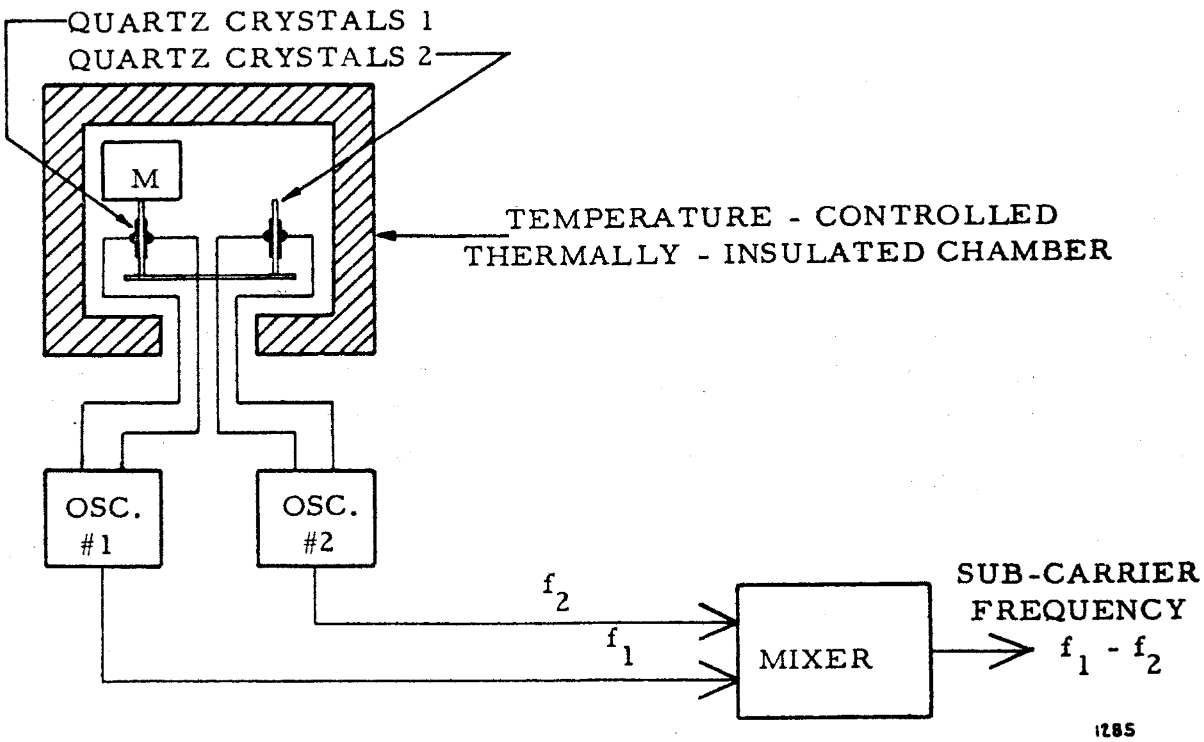

Figure 23. Schematic Of A Piezo-Electric Gravity Meter

*Proc. IRE, Vol. 48, 244-245, 261-262, Vol. 49, 1950.

With temperature stabilization and careful mechanical design, a relative frequency stability of 1×10^{-9} for oscillator No. 1 may be achieved. If 3rd overtone 32 megacycle crystals are used, and are ground so that their frequencies after aging are nearly identical, the addition of a force of 1 newton on crystal No. 1 will cause a frequency shift of about 550 cycles per second. This is the difference frequency appearing at the output of the mixer.

If the mass M is such that the moon gravity will cause this force of 1 newton on the edge of crystal number 1, the difference frequency of 550 cycles per second is equivalent to the lunar gravity value of about 162 gals.

The resolution of the instrument is limited by the stability of the two crystals. Using the value of 10^{-9} for the relative stability of oscillator No. 1, the minimum detectable gravity change will be 10 milligals. This will correspond to a frequency change of about 0. 03 cycles per second which can be detected by totaling the difference frequency over a 30-second period.

This design does not lend itself readily to a shock-resistant instrument. A mechanism would be required to remove the mass from the crystal and anchor it firmly during take-off and landing. The quartz wafers themselves will probably also require temporary support to withstand the landing shock. These mechanical manipulations required to protect the element against shock would also cause calibration errors to a varying degree, and the theoretical accuracy of 10 milligals would probably not be realized. It is not likely that a quartz crystal would maintain its original oscillation frequency within the required 0. 03 cycles per second after being subjected to various stresses and shock loadings.

The operating environment would require close temperature control to detect the slight frequency change caused by gravitational variations. Even with selected crystals, the deviation from perfect temperature tracking over even a few degrees would probably exceed 0. 03 cycles per second. Optimistically, a $\pm 1^{\circ}$ C temperature excursion could be tolerated.

3. Gradiometer

When considering the possible methods of measuring lunar gravity the vertical gravity gradiometer must be considered. However, it is believed that the development of such an instrument for this purpose is probably several years in the future.

A vertical gradiometer, as the name indicates, is an instrument for measuring the second order variation of gravity in a nominally vertical direction. It is comparable to the well known horizontal torsion balance, which, if it could be "laid on its side" would actually measure the

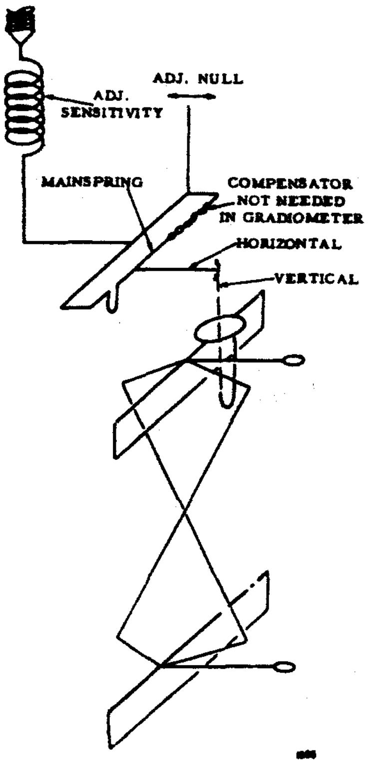

Figure 24. Schematic Of A Fused Quartz Vertical Gradiometer

vertical gradient. In other words, the variation in the "free air" correction as applied to gravity measurements could be directly measured. The two main advantages of such an instrument are: (1) the instrument is insensitive to vertical acceleration, and so could be read while in motion or in an unstable environment, and (2) the values of gradient are independent of elevation so that no correction for elevation is required. Gravity measurements can be obtained from values of vertical gradient by integration.

The state of the art for vertical gravity gradiometers is presently in an early stage. A successful fused quartz instrument has been produced in the laboratory and the gradient has been directly measured; however, a great deal of experimental work must be done before a field-worthy instrument for terrestrial use is in hand. For this reason and for reasons of its probable greater size, weight, and fragility it is our opinion that the gradiometer be reserved for later use in lunar exploration.

A brief description and schematic diagram of the prototype instrument is given below.

The vertical gravity gradiometer includes a "pair" of masses supported on separate suspensions for rotation about their respective horizontally disposed, vertically displaced axes. The two suspensions are interconnected by their flexible crossed numbers such that mechanical amplification of any difference between the force experienced by the two masses causes a net rotation of both masses, one opposite the other. An astatizing system is coupled to the assembly, with a read-out device for null reading the displacements (See Figure 24).

(TI Patent Case #TI-1418)
Not Filed Yet

The gradiometer should have the same resistance to shock damage as the regular quartz gravity meter, since it is made of the same material. Its temperature coefficient is effectively zero, since it is in principle a comparison of two systems at a slightly different location. Any effect on our system caused by temperature, drift, radioactivity, etc., is canceled when the reading is compared to that of the other system.

The disadvantage of the gradiometer is that it will necessarily have a vertical dimension considerably larger than that of a gravity meter. This is inherent in a gradiometer because it must sense a force at two different points in order to yield the rate of change of that force. A second disadvantage is that while the gradient as well as the forces of gravity is related to local structure, the influence of matter on the gradient decreases as the inverse cube of the distance. This means that the gradient measurement made at a first-landing location would provide less fundamental knowledge than lunar gravity measurements. In later exploration stages, however, it might be quite useful to have a gravity instrument sensitive to near-surface structures and which does not require precise leveling.

D. COMPARISON

The following table is a summary of the relative merits of different kinds of gravity meters with respect to hard-landing lunar meter requirements. The grades are excellent (e), good (g), fair (f), poor (p), not at all (0) and unknown (?).

REQUIREMENT \ TYPE	SPRING		PENDULUM	VIBRATORS			GRADIO-METER
	QUARTZ	METAL		STRING	PIEZO-RESISTANT	PIEZO-ELECTRIC	
SHOCK RESISTANCE	e	f	e	g	g	p	e
TEMPERATURE STABILITY	g	p	e	p	g	p	g
ACCURACY	g	e	f	f	f	f	f
CALIBRATION RELIABILITY	g	p	e	g	?	p	f
DRIFT	g	e	e	f	?	?	e
ADAPTABILITY TO TELEMETERING	g	g	e	g	e	e	g
ACCURATE LEVELING	g	g	e	g	e	e	f
MINIATURIZATION	e	f	f	f	e	e	f
OPERATION IN SEISMIC MOTION	f	f	f	g	g	g	g
OPERATION IN TRANSPORT MOTION	p	g	f	g	g	g	g
STABILITY IN RADIATION	f	?	g	?	?	?	f
STABILITY IN MAGNETIC CHANGES	e	p	e	f	g	g	e
STATE OF DEVELOPMENT LUNAR USE	g	f	p	p	p	p	p

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APPENDIX A

CALCULATION OF VARIATION IN TIDAL FORCE

Heiland (1946, p. 164) shows that the vertical component of tidal force due to a heavenly body of mass M at a distance d from an observing body whose radius is R will be given by

$$\Delta g = -\frac{3k\,MR}{2d^3}\left(\cos 2\theta + \frac{1}{3}\right)$$

where θ is the zenith distance and k is the gravitational constant.

For the maximum tidal force on the moon, $\theta = 0$ and for the difference, take the maximum and minimum distances 4.06 and 3.56 x 10^5 km. Then

$$\Delta g = 2kMR\left(\frac{1}{d_2^{\,3}} - \frac{1}{d_1^{\,3}}\right)$$

and if M = 5.98 x 10^{27} gr. and R = 1.738 x 10^{8} cm.,

$$\Delta g = 1.0 \times 10^{-3}$$

APPENDIX B

SURVEYING PROBLEMS ON THE MOON

I. CURVATURE

Considerable mention has been made in the literature of the problem of curvature on the moon in terms of limiting the length of line-of-sight measurements, both electronically and visually. This limitation is illustrated by Figure B-1, showing the curvature curve for the moon, and the curvature-refraction curve for the earth. A rule of thumb is: For a given altitude the maximum visibility on the moon is only 49% of the maximum on the earth.

This disadvantage, however, is offset by the increased visibility of illuminated objects on the moon because of freedom from atmospheric disturbances. It should be possible to secure valid trignometric measurements on the moon much more quickly than on earth for this reason.

If trignometric leveling in conjunction with electronic distance measurements is substituted for stadia-level gravity surveys currently used on earth, an antennae-flashing beacon tower 100 feet high could reference location and elevation differences over a radius of more than five miles to an accuracy of plus or minus 0.6 foot, assuming a theodolite angle-measuring capability of 5 seconds.

Another consideration on the moon is that although the line-of-sight distance is much less than on earth, the percentage of the moon's area that can be observed from a given altitude is much greater than the percentage of the earth's area. The area of the moon is on the order of 38×10^6 square kilometers as compared with 510×10^6 square kilometers for the earth. From an elevation of 4572 meters (15,000 feet) the line-of-sight distance on the moon is about 126 kilometers, and on the earth, 258 kilometers. On the moon, however, the area brought under observation would be about 1.29% of the moon's surface as compared with about 0.41% of the earth's surface.

II. LACK OF SEA LEVEL REFERENCE

Elevation reference around the margin of an ocean, sea or lake on earth can be made by ties to tide gauges, which saves time. This convenience will not be available to reference individual surveys around the margins of marias on the moon. To reference accurately individual surveys, some method must be devised to secure "elevation" differences between them either by trigonometric leveling or by some satellite tracking technique.

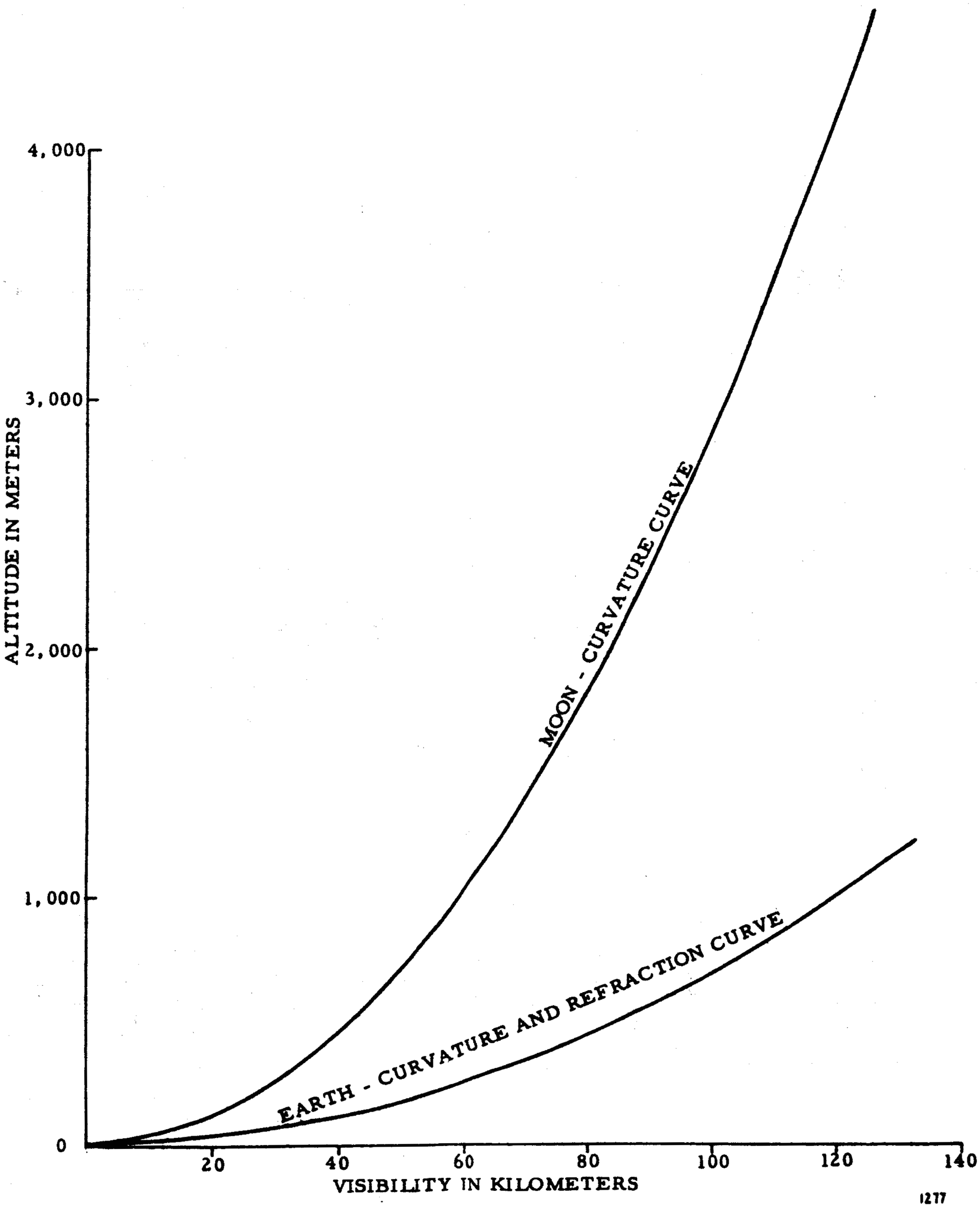

Figure B-1. Altitude vs Maximum Visibility Curves For Moon And Earth

III. DEFLECTION OF THE VERTICAL

If we assume anomalous masses on the moon of the same order of magnitude as on the earth, deflection of the vertical (and therefore the error in leveling due to the deflection) will be six times as great as in a similar situation on the earth. Depending somewhat on the state of lunar isostasy, this error could be as great as 6 minutes of arc. (See Figure B-2)

IV. MAGNETIC NORTH REFERENCE

Local surveys on the earth are referenced to magnetic north and the local declination. If satellite data acquired by the Russians is reliable, there may not be a magnetic field large enough on the moon to orient a magnetic compass needle. "North" reference may have to be made by means of a gyroscope oriented by star shots.

V. MOON SHADOWS

Because of the lack of atmosphere and consequent lack of light diffraction, shadows on the moon will be deep and dark. Instrument dials, note book headings, stadia markings, and so forth could not be read without the assistance of artificial light.

VI. MISCELLANEOUS

The above problems may be minor compared with the problem of surveyor survival and movement on the moon. Many other problems need to be considered including instruments which can be used by an operator encumbered by a space suit.

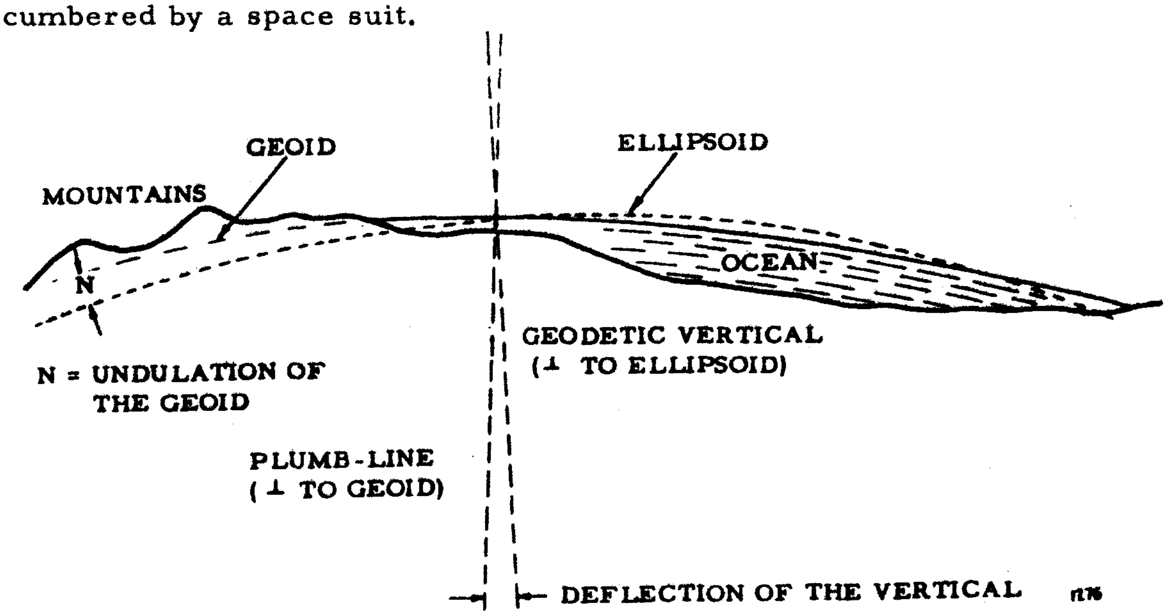

Figure B-2. Effect Of Ocean Basins And Land Masses On Undulation And Deflection

APPENDIX C

EXTRACT FROM TEXAS INSTRUMENTS PROPOSAL NO. A63-93

Proposal to Develop a Precision Miniature Accelerometer For Low g Environment

EXTRACT

SECTION III

TECHNICAL APPROACH

Our approach to solving the problem as outlined in Section II is to produce the least complicated instrument capable of doing the job. Because of this approach, this proposal will be limited in discussion to two transducer types which, we believe, are entirely applicable. One method is based on the piezoresistive effect in basic monocrystalline silicon material. The second method is based on ferromagnetic resonance in evaporated permalloy films. Each method is discussed in the following paragraphs.

A. SOLID-STATE ACCELEROMETER USING THE PIEZORESISTIVE EFFECT IN SILICON MATERIAL

Texas Instruments has been active in the development of solid-state accelerometers for several years. A description of our transducer capability appears in Section VI.

Piezoresistivity is a basic property of monocrystalline silicon material, mainfesting itself as a change in electrical resistance proportional to an applied stress. The first commercial application of this effect was the development of the semiconductor strain gage. The measure of strain gage sensitivity is the "gage factor" and is defined as follows:

$$G = \frac{1}{\epsilon} \frac{\Delta R}{R} = \frac{Y}{\sigma} \frac{\Delta R}{R} \tag{1}$$

where

G = gage factor

ϵ = strain = $\frac{\Delta L}{L}$ (L = zero stress length)

R = zero stress resistance

Y = Young's modulus

σ = stress.

The gage factor of present wire strain gages is about 2. Semiconductor strain gages have gage factors from 50 to 200, dependent upon the impurity doping levels and crystal axis orientation and temperature.

Strain gages are made from bulk silicon material of relatively low resistivity. The overall resistance of the gages is controlled by the physical dimensions of the bar and is normally limited to about 200 ohms. The low resistance, in turn, limits the magnitude of voltage which can be applied to the device because of self heating, preventing full exploitation of the piezoresistive properties without laboratory-type measuring equipment.

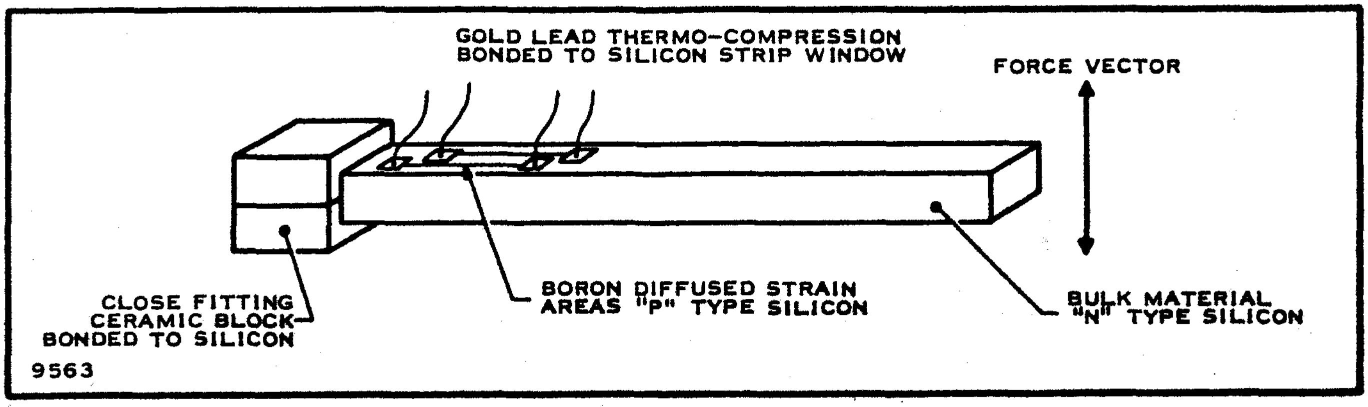

Figure 1. Texas Instruments Diffused-Layer Strain Member

Figure 1 illustrates Texas Instruments technique for manufacturing silicon elements whose resistance and physical dimensions are independently variable. The bar itself is "n" type silicon bulk material. Two "p" type strips are diffused into the surface of the bar. Electrical isolation between strips is provided by the p-n junction between the strip and substrate, allowing use of ac or dc energizing voltage.

Temperature changes affect the silicon element by (1) producing an overall resistance change in the silicon strip and (2) changing the gage factor. Through the temperature range of interest the silicon material exhibits a near linear positive temperature coefficient. Figure 2 illustrates the temperature dependence of gage factor (presented as piezoresistive coefficient) for silicon of several impurity concentrations.

1. Accelerometer Design

Silicon elements of the configuration shown in Figure 1 can be considered rectangular beams and used with the simple beam formulas. We have built accelerometers using the beams in direct tension and as cantilevers. Figure 3 illustrates the cantilever configuration as used in our acceleration switch. The axial stress design is shown in Figure 4. Normally two bars are used with two diffused strips each so that a four-active-element bridge circuit can be constructed.

Viscous damping has been applied to all designs. In the acceleration switch a compensated damping system effectively maintains the damping coefficient nearly constant through a temperature excursion of 150°C. Gas damping is also applicable to the design.

An accelerometer of similar design to that of Figure 3 whose dynamic range is 10^{-4} to 10^{-6} g is possible, and its performance can be calculated using standard beam formulas.

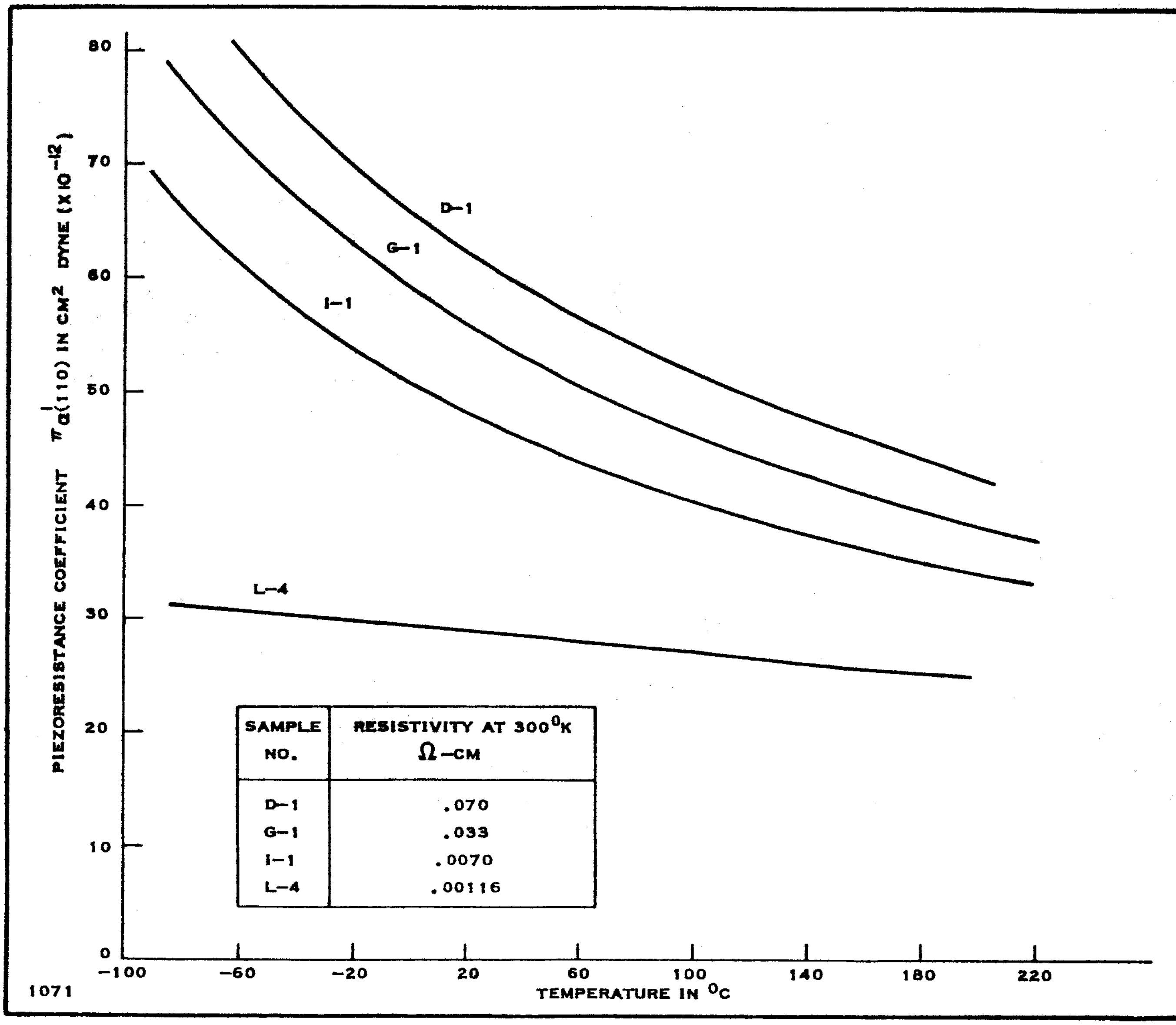

Figure 2. Piezoresistive Coefficient as a Function of Doping and Temperature

The force produced by a mass acted upon by the earth's gravitational field is:

$$F = MA = \frac{w}{g} A \tag{2}$$

where

A = the acceleration

w = weight of the mass.

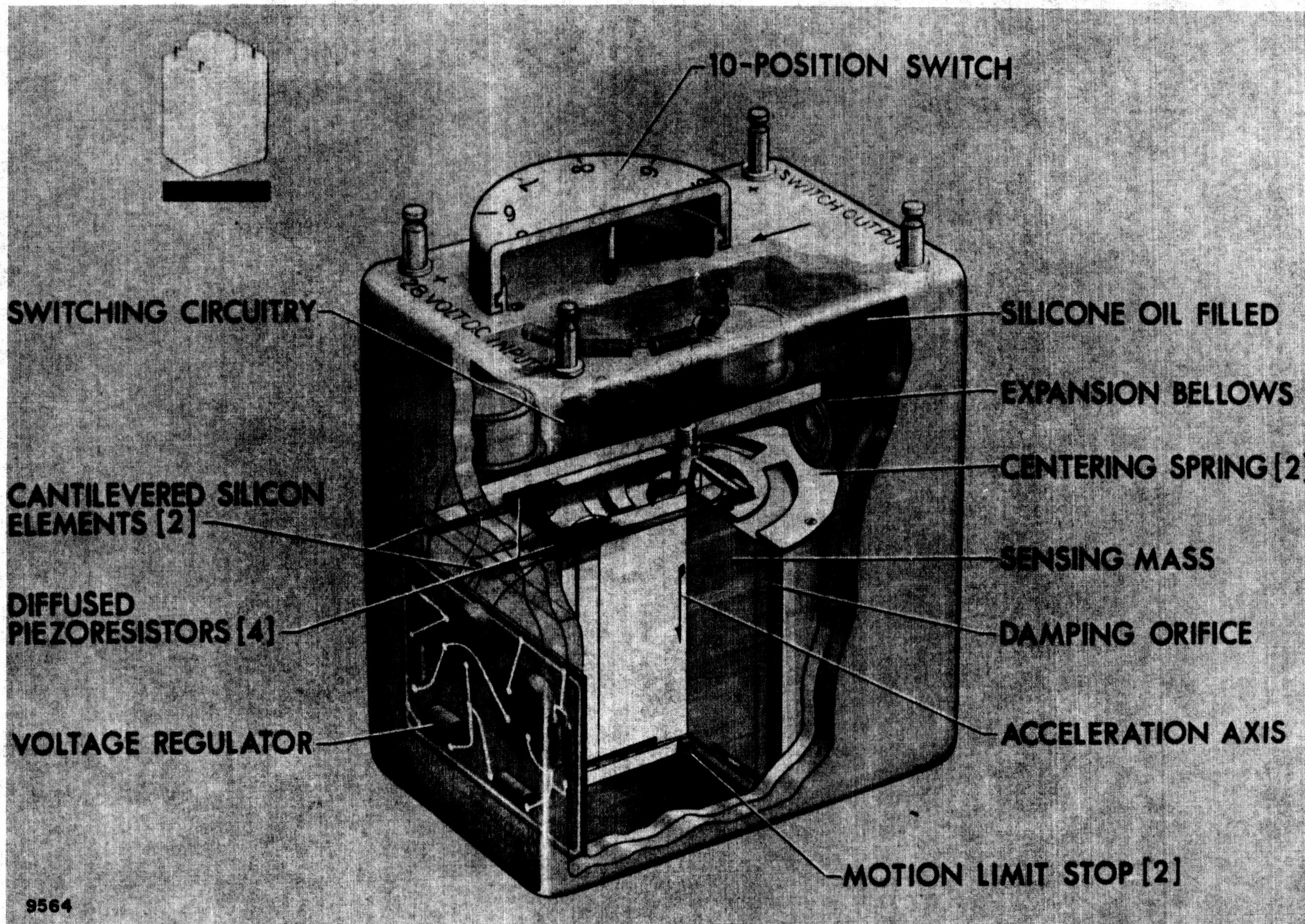

Figure 3. Piezoresistive Accelerometer

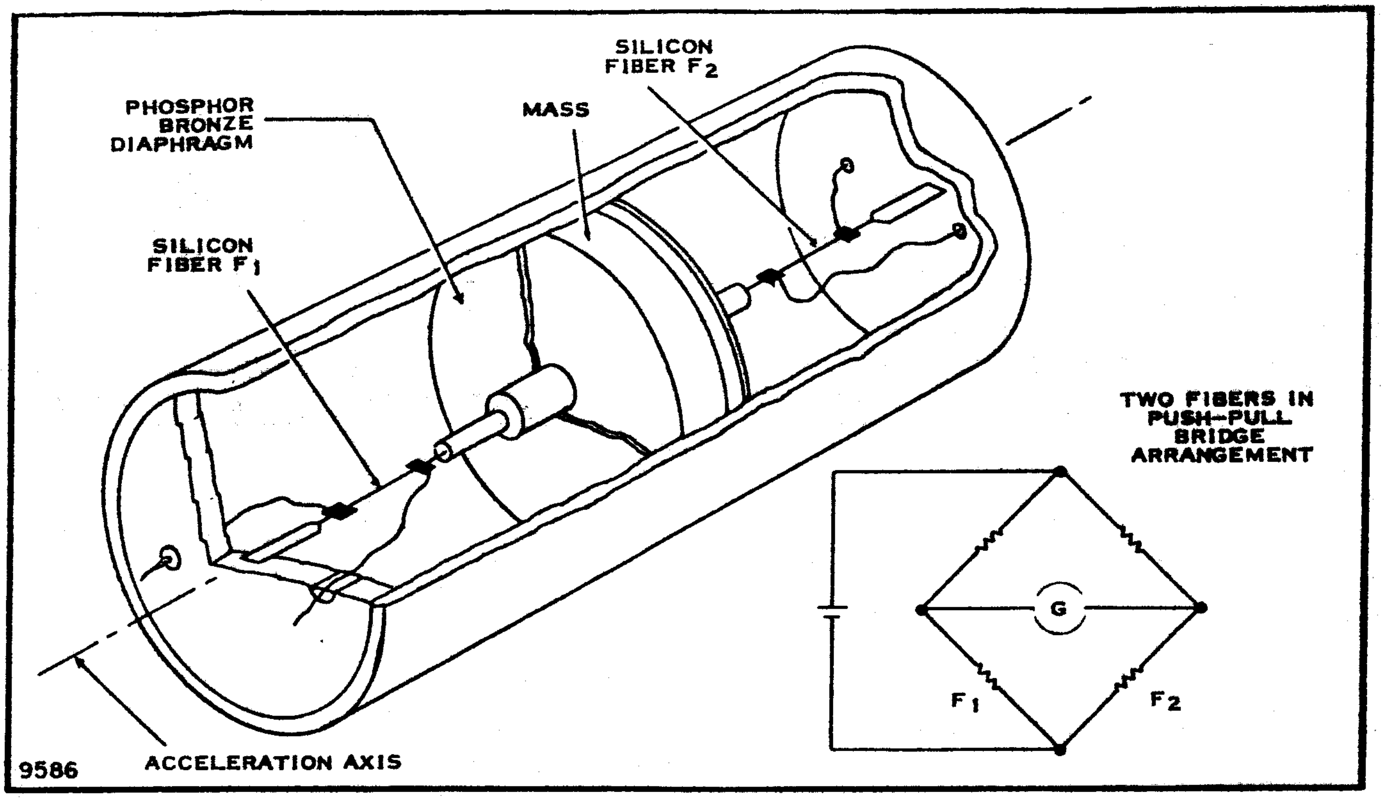

Figure 4. Experimental Model of Uniaxial Accelerometer

Then for an acceleration of 10^{-6} g

$$F = \frac{w}{g}(10^{-6}\ g) = w \times 10^{-6}. \tag{3}$$

The stress in the extreme fibers of a beam mounted as a cantilever is represented by

$$S = \frac{MC}{I} \tag{4}$$

where

S = stress

I/C = section modulus of a beam

$M = FL$ = bending moment = force x beam length.

The stress imposed on the accelerometer ctive beam is then:

$$S = F\left(\frac{LC}{I}\right) = w \times 10^{-6}\left(\frac{LC}{I}\right) \tag{5}$$

where the term in parentheses pertains to the physical dimensions of the silicon beam.

Assume a silicon beam with the following dimensions:

Length	$L = 1$ in.
Width	$b = 0.2$ in.
Thickness	$h = 0.004$ in.

Then

$$\frac{C}{I} = \frac{6}{bh^2} = 1.875 \times 10^6$$

and

$$S = 1.875\ w.$$

Now assume w = 3 lb,

$$S = 5.625\ \text{lb/in.}^2.$$

Through the range of this accelerometer's operation, the active element would be stressed from 5.625 lb/in.^{2} to 562.5 lb/in.^{2}. The unamplified voltage output of the device with the strain elements arranged as a four-active-element bridge can now be calculated.

Using Equation (1) with $Y = 27.15 \times 10^6$ PSI (Young's modulus for silicon) and assuming a gage factor of 100, we have

$$\frac{\Delta R}{R} = \frac{100\,(5.625)}{27.15 \times 10^6} = 20.7 \times 10^{-6}.$$

For a four-active-element bridge the voltage output is given below:

$$e_o = E\frac{\Delta R}{R} \tag{6}$$

where

e_o = voltage output

E = voltage input.

Then, if we assume an input voltage of 20 volts,

$$e_o = 414 \text{ microvolts at } 10^{-6}\,g \text{ acceleration.}$$

The output at 10^{-4} g would be 100 times greater or 41.4 millivolts. For the required $\pm 3 \times 10^{-8}$ g accuracy, ±12.42 microvolts will have to be detected.

It would be desirable to increase this output by a factor of 20 or more, and accelerometer designs which use mechanical leverage could be used to advantage. Figure 5 illustrates one method which could be used to obtain considerable mechanical advantage for straining the semiconductor elements to higher stress levels. The illustrated configuration would use the inertial mass as a piston. The piston is centered in a cylinder with two

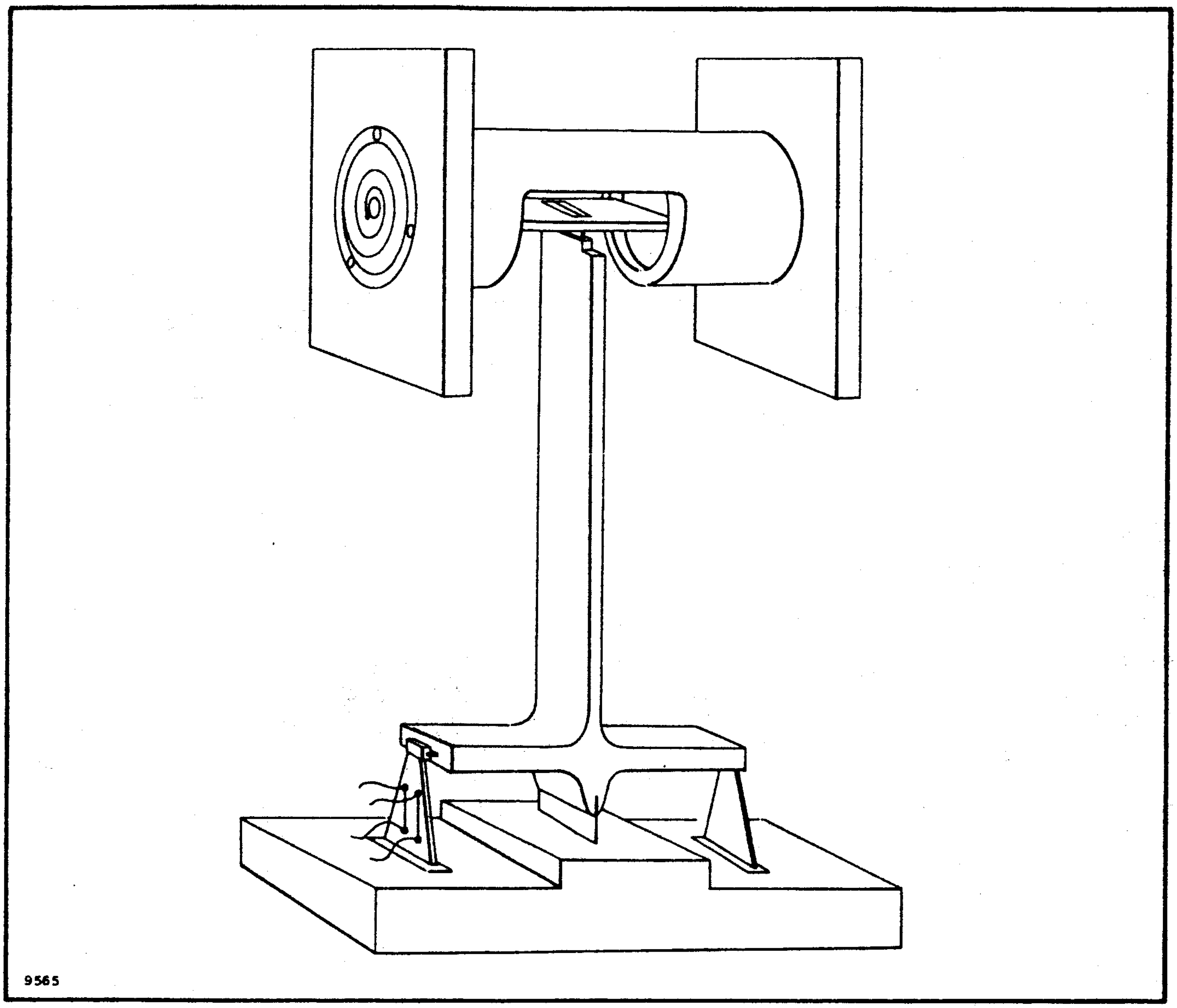

Figure 5. Accelerometer Design Using Mechanical Amplification

spiral springs, allowing almost unrestrained freedom along one axis and heavy restraint in all other directions. The piston-cylinder arrangement is used for damping and is convenient in designing positive stops. All pivots are of the flexure type. The piezoresistive elements are shown as constant strength cantilevered beams.

Other systems for obtaining mechanical advantage are applicable and will be studied carefully.

The relatively large mass of the accelerometer, necessary in this design for the g range indicated, will require adequate damping and positive stops to prevent damage to the sensitive semiconductor elements during shock and vibration testing. Texas Instruments has developed an oil damping system

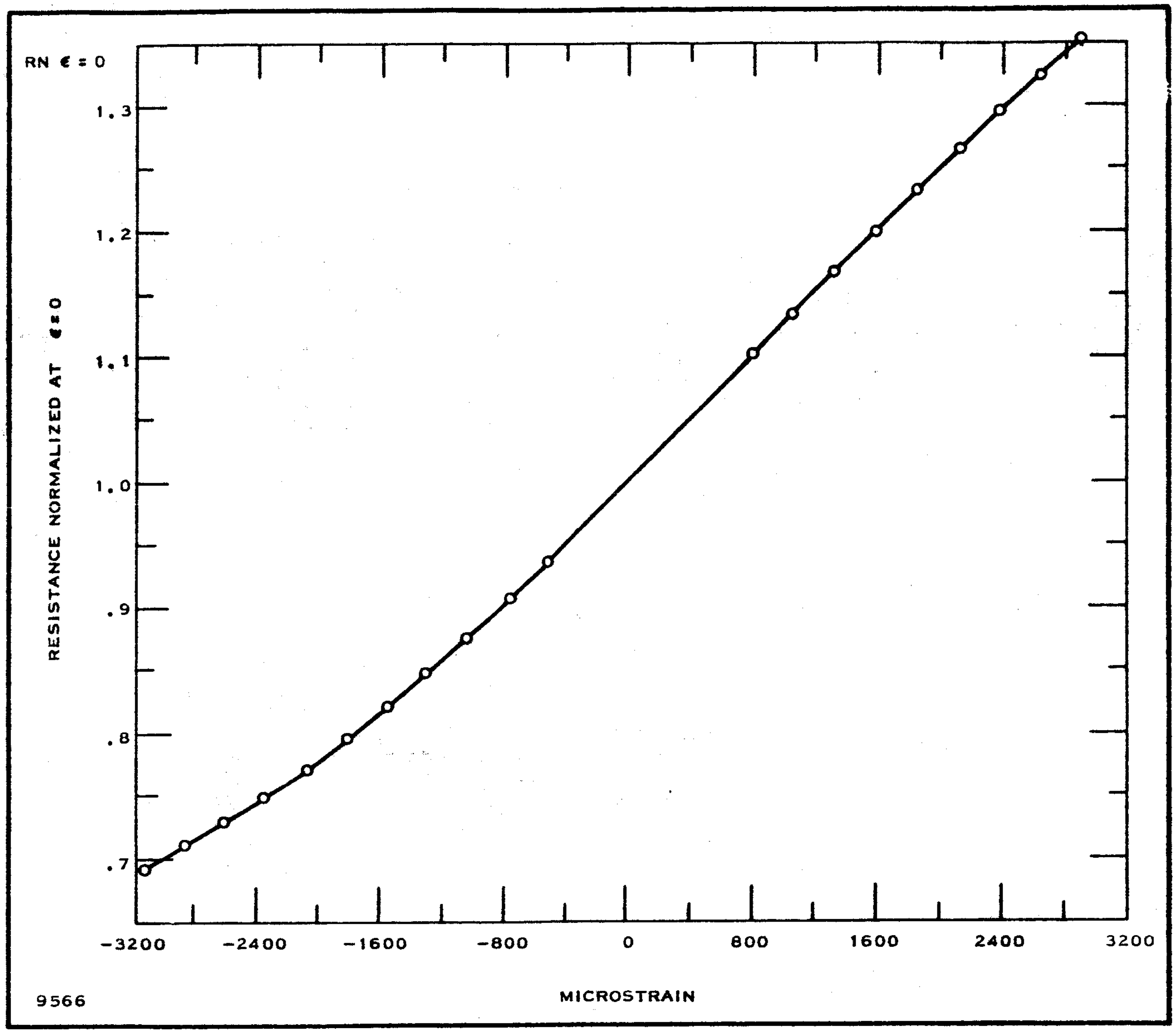

Figure 6. Resistance Vs. Strain for Bulk Semiconductor Strain Gage

which uses a low thermal expansion coefficient metal combined with a high-expansion nonmetal. The resultant function of this combination very nearly counteracts the viscosity-temperature characteristic of low viscosity silicone oil.

2. Test Results

a. Linearity

Tests have been made at Texas Instruments on solid-state accelerometers and piezoresistive semiconductor samples. Figure 6 illustrates the linearity achieved by semiconductor strain gages. The stress level for an

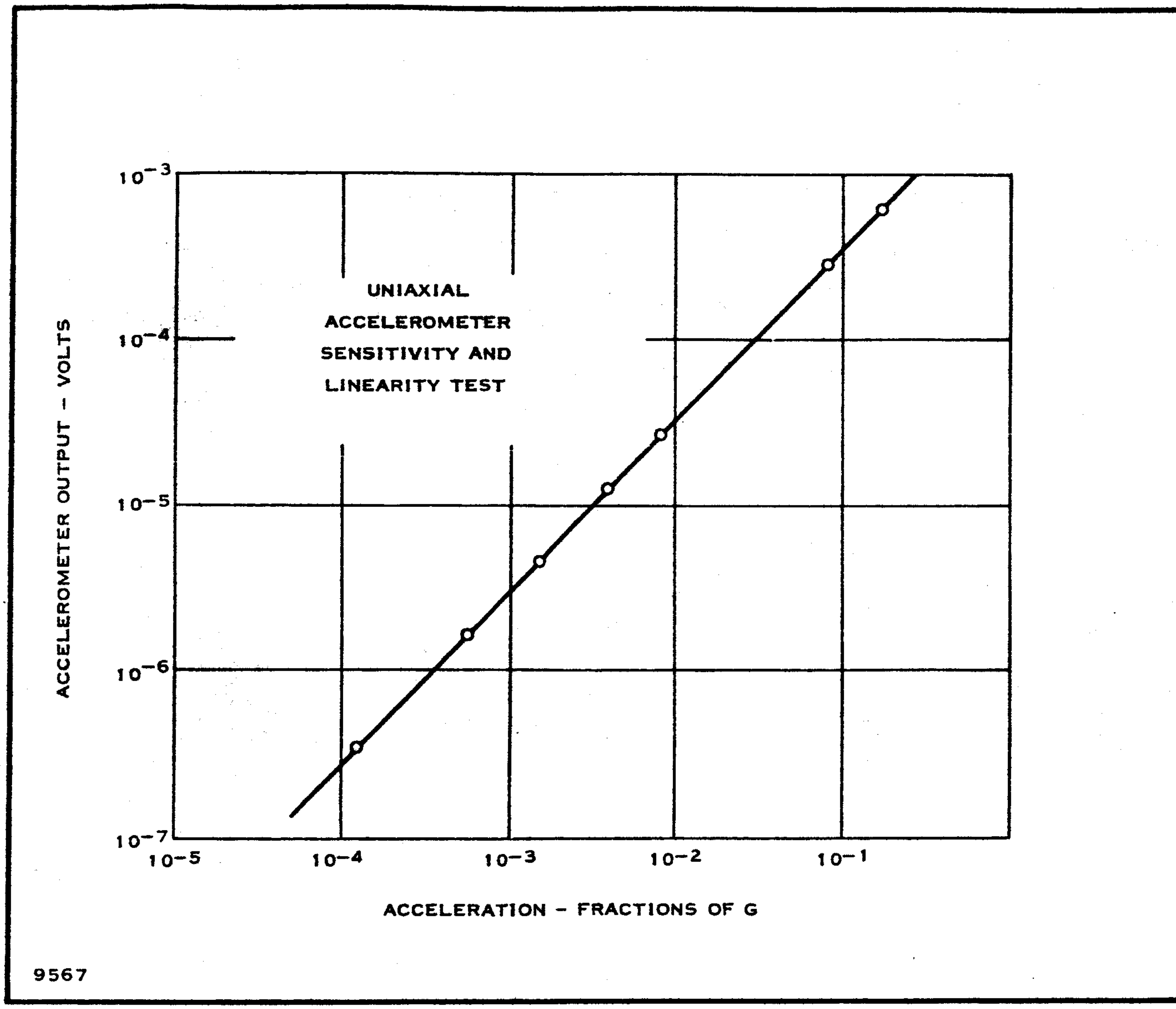

Figure 7. Measured Voltages Out of Uniaxial Accelerometer Bridge as a Function of g

accelerometer should be limited to ±1600 microstrain to maintain operation within the extremely linear portion of the curve. Figures 7 and 8 illustrate the linearity achieved with two engineering model accelerometers. No departure from linearity is observable within the operating range.

b. Resolution

Resolution of the semiconductor gage can be considered almost infinite since it is degraded only by the internal noise of the gage itself. It was shown by Mason *et al.*[1] that a highly doped strain gage with a resistance of

[1] W. P. Mason, J. J. Forst, and L. M. Tornillo, "Recent Developments in Semiconductor Strain Transducers," ISA 15th Annual Instrument-Automation Conference.

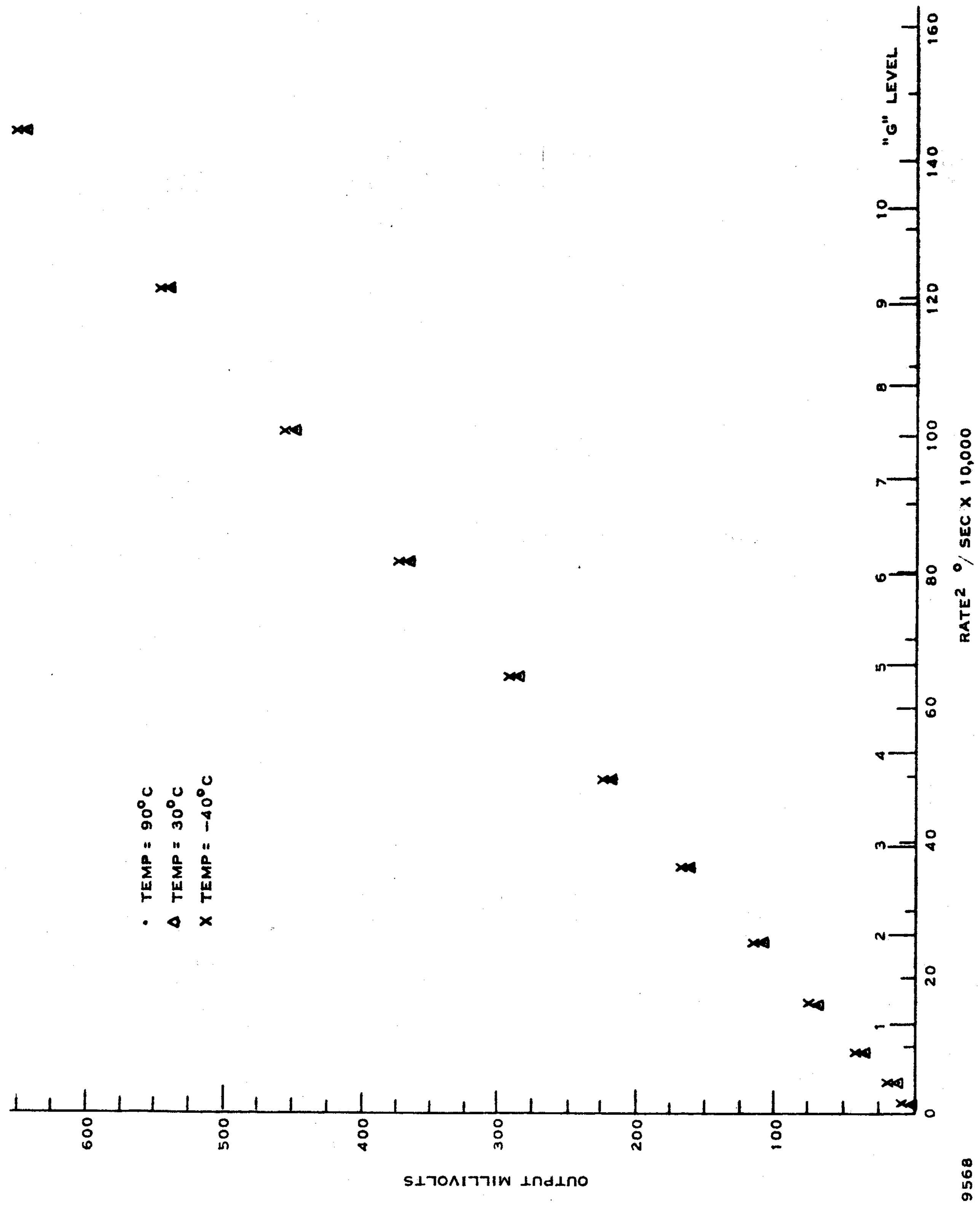

Figure 8. Accelerometer Output Vs. Acceleration at Three Temperatures

100-ohms, a gage factor of 50, a current flow of 10 ma, and a frequency band from 0–1 cps will have thermal noise equal to 1.20×10^{-9} volt. The other dominant noise, termed "fluctuation noise," is a function of the element geometry, frequency, and power dissipation. It is minimized by making the element with a large surface-to-volume ratio and can be reduced to a portion of the thermal noise. The previous design example showed an accelerometer output of 414×10^{-6} volt at 10^{-6} g. At an acceleration of 10^{-8} g, considering thermal noise only, the signal-to-noise ratio would be approximately 3500:1.

c. Hysteresis

Hysteresis in the silicon material itself should be very small, since it is of monocrystalline structure. Any measurable hysteresis of the unit can be attributed to that contributed by the flexural pivots and the mass restraining springs. Good mechanical design can keep hysteresis down to a very small portion of the overall system error.

d. Thermal Sensitivity

Temperature sensitivity of the piezoresistive element is the greatest problem in the design of high-accuracy transducers. Figure 2 shows the temperature sensitivity of elements of several different doping levels. A silicon element with the impurity concentration represented by curve L-4 would have a gage factor of 60 and would exhibit a minimum of sensitivity change with temperature.

The strip resistance of the highly doped silicon material has a positive temperature coefficient of approximately 0.1 percent per degree centigrade and is linear.

Figure 8 illustrates the temperature sensitivity of a compensated engineering model accelerometer with a 0–10 g range. As shown, the maximum static error band for the unit is ±1 percent for a temperature excursion of 130°C. The maximum error of this unit is 13 millivolts out of a full-scale device output of 650 millivolts. The connotation is that at a lower output voltage a much better temperature compensation must be achieved if an overall accuracy of $\pm 3 \times 10^{-8}$ g is to be attained. A computer program will be required to select the compensation network which best fits the thermal characteristic curve of each individual accelerometer. The limited operational temperature requirements will make this method of compensation entirely practical.

3. Ultimate Accuracy of Piezoresistive Device

The ultimate accuracy of a semiconductor strain gage was calculated by Mason et al.[1] He assumed a signal-to-noise ratio of 10:1 and calculated a minimum detectable strain of 2.6×10^{-10} for a gage with a gage factor of 50. Substituting 2.6×10^{-10} and 50 in Equation (1) produces a $\Delta R/R = 0.013 \times 10^{-6}$.

[1] Ibid.

Assuming a four-active-element bridge with an input of 20 volts and using Equation (6), we find

$$e_o = 20\,(0.013 \times 10^{-6}) = 0.26 \text{ microvolt.}$$

These calculations were made on highly doped silicon material. Previous calculations made for a low g accelerometer assumed a slightly lower doping level, hence a higher gage factor (100) and slightly higher noise level. However, the difference in minimum detectable strain would be slight and the value calculated would be extremely small compared to the accuracy requirements.

4. Electronics Required

The output of the piezoresistive accelerometer will require amplification to provide a 5-volt full-scale output. Two amplifier designs will be studied: (1) a stabilized and compensated differential dc amplifier and (2) a chopper stabilized amplifier. Through the use of mechanical leverage, the full-scale output of the solid-state accelerometer could be increased to approximately 0.5 volt. With an amplification of 10, the dynamic range of the system would be from 50 millivolts at 10^{-6} g to 5 volts at 10^{-4} g. A properly designed differential amplifier with a gain of only 10 has the capability of providing the required accuracy With the limited operational temperature range, the use of a chopper stabilized operational amplifier does not appear necessary at this time.